SGW-42305
Revision 0

Collection and Mapping of Water Levels to Assist in the Evaluation of Groundwater Pump-and-Treat Remedy Performance

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

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Terms

CFM	capture frequency map
CY	calendar year
gpm	gallons per minute
OU	operable unit
RK4	Runge-Kutta numerical integration scheme

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Equation Notations

NOTE: Consistent units are assumed throughout.

General Terms:

x	=	easting or X ordinate
y	=	northing or Y ordinate
h(x)	=	estimated elevation at location (x)
h(x,y)	=	estimated elevation at location (x,y)
m(x)	=	mean value at location (x)
m(x,y)	=	value of smoothly varying trend or drift at location (x,y)
ε (x)	=	error or residual at location (x)
ε (x,y)	=	residual from the drift at location (x,y)
a, b, c	=	regression coefficients for the linear drift

Point Sink/Source of Known Strength:

r	=	radial distance from the pumped well
π	=	pi (3.14159…)
R	=	radius of influence
Q	=	pumping rate
s_r	=	drawdown at radial distance r due to pumping at rate Q
T	=	aquifer transmissivity

Line Sink/Source of Known Strength:

L	=	length of the line sink/source
σL	=	discharge per-unit-length
Ω	=	complex discharge potential
Z	=	dimension-less complex variable
$z1$	=	complex ordinate of one end of the line sink/source
$z2$	=	complex ordinate of the other end of the line sink/source
z	=	$x + iy$ is the point where Z and Ω are evaluated

Circular Source of Known Strength:

x_j, y_j	=	ordinates of the center of the j^{th} circular source
r_j	=	radius of point (x,y) from the center of the j^{th} circular source
R_j	=	radius of the j^{th} circular source
∞	=	infinity

Generalized Regression Equation:

d	=	regression coefficient for point sink/source drift term, if included
$Q_i(r)$	=	drawdown factor due to the i^{th} sink/source at distance r
$\sum_{1}^{m}$	=	summation from 1 to m where m = the number of point sink/sources
e	=	regression coefficient for line sink/source drift term, if included
$L_i(r)$	=	drawdown factor due to the i^{th} line sink/source at distance, r
$\sum_{1}^{n}$	=	summation from 1 to n where n = the number of line sink/sources
f	=	regression coefficient for circular source drift term, if included
$P_i(r)$	=	mounding factor due to the i^{th} circular source at distance r
$\sum_{1}^{o}$	=	summation from 1 to o, where o = the number of circular sources

Particle Tracking:

V (x,y)	=	groundwater velocity
K	=	hydraulic conductivity
i	=	hydraulic gradient
n_e	=	effective porosity

1 Introduction

A variety of techniques exist for estimating the capture zone developed by one or more pumped wells, including mass balance approaches, analytical and numerical models, and methods based on mapping of measured water levels (*Groundwater Contamination Optimal Capture and Containment* [Gorelick et al. 1993]; EPA/542/R-02-009, *Elements for Effective Management of Operating Pump and Treat Systems*; EPA 600/R-08/003, *A Systematic Approach for Evaluation of Capture Zones at Pump and Treat Systems: A Final Project Report*). Regardless of the approach used to infer capture, the analysis requires some understanding of groundwater flow directions and rates, as well as the response of the aquifer to pumping. This must be inferred directly or indirectly through measurements of groundwater levels. This document describes a method for preparing groundwater-level maps that can improve the inference drawn from those data that can be used to help estimate the extent of hydraulic capture developed by groundwater pump-and-treat remedies.

1.1 Pump-and-Treat Design and Hydraulic Capture

Conventional pump-and-treat systems are based on the concept of extracting contaminated groundwater for treatment at the surface. The treated water is typically returned to the aquifer via wells, or it is discharged to a surface water body or sewer system. Pump-and-treat systems can be designed with the objective of containment (when extraction rates are sufficient to prevent further migration and protect potential receptors) and/or restoration (when extraction rates are typically more aggressive to achieve aquifer cleanup) (*Alternatives for Ground Water Cleanup* [National Research Council 1994]; *Overview of Groundwater Remediation Technologies for MTBE and TBA* [ITRC 2004]). One advantage of pump-and-treat over some of the other remedies is the concept of hydraulic control (i.e., active pumping can alter groundwater flow directions to prevent further migration of contaminants, providing some assurance that potential impacts to human and/or ecological receptors can be mitigated or eliminated).

Principal questions to be answered in the design and optimization of pump-and-treat systems include the following (modified after "Capture-Zone Type Curves: A Tool for Aquifer Cleanup" [Javandel and Tsang 1986]):

- What is the optimum number of pumping wells?
- Where should each pumped well be located and screened?
- What is the optimum pumping rate for each well?

These design variables are largely determined by first understanding the extent of the contaminated groundwater, and then estimating the location and extent of the capture zone required to contain and recover the contamination. The capture zone is defined by a three-dimensional, bounding surface that divides groundwater that will ultimately be extracted by the pumping system from groundwater that will not be extracted by the pumping system. The capture zone is a different concept to the "area of influence" or "cone of depression," which are generally used to describe the area (volume) of aquifer where water levels change measurably in response to pumping.

Evaluation and optimization of an operating remedy typically focus on understanding and then improving upon one or more features of the remedy (e.g., pumping rates) in order to accelerate the attainment of one or more remediation goals (e.g., cleanup times) while reducing lifecycle costs. While formal optimization techniques suitable for use with numerical models have been successfully applied to pump-and-treat systems (Gorelick et al. 1993; "A Field Demonstration of the Simulation-Optimization Approach for Remedial System Design" [Zheng and Wang 2002]; EPA/542/R-02-009), rigorous analysis of monitoring data (in particular, measured water levels) without the use of sophisticated models often complements or verifies these analyses.

1.2 Various Roles of Water-Level Data

Water levels measured in wells are a common element of monitoring programs that are designed to infer the performance of pump-and-treat remedies. Measured water levels may be used directly (e.g., to calculate hydraulic gradients or to prepare potentiometric maps) or indirectly (e.g., to help calibrate the parameters of a groundwater model). Measured water levels may also be used to prepare hydrographs to evaluate time-varying responses of the aquifer and/or to estimate aquifer properties using methods such as those described in *Theory of Aquifer Tests* (Ferris et al. 1962). The use of water levels beyond the preparation of maps to estimate flow directions and rates, and to infer the extent of capture, are beyond the scope of this document.

Maps of groundwater levels are often prepared to understand the approximate directions and rates of groundwater flow, as well as the corresponding directions and rates of contaminant migration. Water-level maps are sometimes prepared manually (i.e., hand-drawn) by an experienced hydrogeologist, or one of a variety of automated interpolation techniques may be used. One advantage of hand-drawn maps is that the hydrogeologist can impart knowledge of the physical setting in the mapping (e.g., the influence of surface water bodies, and boundaries and other features on water levels), while most automated interpolation techniques do not easily permit the enforcement of this kind of independent knowledge. However, automated techniques can produce continuous maps (i.e., grids) that are more consistent and reproducible between different analysts and different data sets, which mitigate some of the subjectivity encountered with hand-drawn maps. Because of their continuous gridded (in-space) output, these surfaces can also be used in particle-tracking analyses.

1.3 Objectives

This document describes a water-level mapping method for estimating the capture zone of pumped wells. This is accomplished by presenting the theoretical basis of the mapping technique, as well as recommendations for implementing the methods described herein. Methods for ensuring data quality and the qualitative and quantitative methods for evaluating the reasonableness of results obtained using the methods described are also discussed. The method enables an experienced hydrogeologist to impart knowledge about some aspects of the physical setting (e.g., the location and rates of pumped wells) when using an automated interpolation technique to prepare water-level maps. The method can be used to evaluate large water-level data sets in a variety of settings. Using this method in the analysis of water-level data can provide information on the performance of the pump-and-treat system and may constitute one of multiple lines of evidence in the evaluation and optimization of remedy performance (EPA 600/R-08/003).

The methods described herein are not suitable for use under all conditions. It is assumed that the technique will be used by an experienced hydrogeologist, with detailed knowledge of the subject site, to assist in preparing water-level maps. This document is intended to provide the hydrogeologist with sufficient information to apply these methods to their site.

1.4 Document Content

Since the mapping method combines kriging with analytical expressions derived from the analytic element method, Chapter 2 provides an overview of a variant of kriging referred to as "universal kriging," followed by an introduction to common analytic expressions that are used in the mapping analyses.

Chapter 3 describes how particle tracking on the mapped water-level surfaces can be used to estimate capture for one or more water-level data sets, and it summarizes some assumptions and limitations of this approach. Chapter 3 also discusses some of the benefits and shortfalls of mapping and numerical modeling techniques for evaluating the extent of capture, reinforcing the concept that multiple lines of evidence should be used to estimate capture.

The discussion in Chapter 4 provides guidance for applying the techniques described, including the data requirements and data processing, as well as interpretation of the results from a mapping analysis. Chapter 5 discusses the spatial distribution of water-level monitoring locations, the monitoring of other features (e.g., pumped wells), and monitoring frequency. Chapter 5 does not provide a comprehensive strategy for designing monitoring programs; instead, it highlights some key elements that should be considered when designing a monitoring program for purposes of evaluating hydraulic capture.

Field examples using these techniques are provided in Chapter 6. The conclusions are provided in Chapter 7, and a list of the references cited in this document is included as Chapter 8.

1.5 Programs for Implementing the Methods Described

Programs that implement the methods described in this document are available free of charge from the following website: http://www.sspa.com/KT3D_H2O. This document does not describe these programs in detail. The programs are distributed with documentation that includes a software user's manual, a discussion of the kriging theory, and a detailed discussion of particle-tracking techniques. Further details on KT3D_H2O are provided in "KT3D_H2O: Software for Kriging Water Level Data Using Hydrologic Drift Terms" (Karanovic et al. 2009)

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2 Theoretical Development

This chapter provides an overview of kriging, as well as common analytic expressions that can readily be combined with kriging. Brief discussions are presented on the use of image theory to depict lateral boundaries, and also the implications of using the method for estimating regional hydraulic gradients. Assumptions and limitations are also discussed.

2.1 Kriging

Kriging is often used to interpolate irregularly spaced measurement data to regular grids suitable for contouring. One advantage of kriging over other interpolation methods is that, in the absence of measurement error or replicates (co-located data), it is an exact interpolator (i.e., it matches, or honors, the measured data). The following references, which are cited in this discussion, provide detailed discussion of kriging:

- *An Introduction to Applied Geostatistics* (Isaacs and Srivastava 1989)
- *Geostatistical Software Library and User's Guide* (Deutsch and Journel 1992)
- *Geostatistics: Modeling Spatial Uncertainty* (Chiles and Delfiner 1999).

2.1.1 Simple and Ordinary Kriging

Two popular forms of kriging employed for interpolating real-value data are simple kriging and ordinary kriging. In simple kriging, the mean of the data, m, is assumed to be constant everywhere and its value known a priori. In ordinary kriging, the mean is assumed to be unknown a priori and is estimated using either all, or some, local (moving) neighborhood of the measured data. The methods described in this document are based on a form of ordinary kriging that is commonly referred to as "universal kriging."

2.1.2 Universal Kriging

In the most common implementation of ordinary kriging, the mean is assumed to be constant and equivalent to the mean of the data where $m = m(x)$. This ordinary kriging estimator, $h(x)$, for water-level estimation is illustrated in Equation 2-1 as the sum of two components (the mean and a zero-mean residual):

$$h(x) = m(x) + \varepsilon(x) \qquad \textbf{(Equation 2-1)}$$

where $\varepsilon(x)$ is the error or residual from the mean.

Ordinary kriging can support a spatially varying mean, which is commonly described as a trend, or "drift." In this document the term "drift" is used synonymously with the term "trend" to describe a pattern that has a deterministic source or can be approximated by deterministic means. The drift is often a low-order linear function of the data ordinates (Deutsch and Journel 1992; "On the Use of a Main Trend for the Kriging Technique in Hydrology" [Volpi and Gambolati 1978]). This kriging approach is commonly referred to as universal kriging, and the drift is often determined as a linear combination of known functions, where the coefficients are unknown a priori and are estimated as part of the kriging process using the measured data ("Generalized Covariance Functions in Estimation" [Kitanidis 1993]; "Geostatistics: Interpolation and Inverse Problems" [Kitanidis 1999]). When a spatially varying mean is incorporated within the universal kriging estimator to interpolate irregularly spaced data in two dimensions, the kriging estimate is illustrated in Equation 2-2 as the sum of two components (the spatially varying mean and a zero-mean error or residual):

$$h(x,y) = m(x,y) + \varepsilon(x,y) \qquad \textbf{(Equation 2-2)}$$

Where unidirectional groundwater flow exists, a condition that is often encountered in deep and/or confined aquifers within regional aquifer settings (Kitanidis 1993), a linear drift is often suitable for mapping groundwater levels. Kriging with a linear drift is available through popular programs such as Surfer™ and TecPlot®. The universal kriging estimator for gridding water-level data in two dimensions using linear drift is shown in Equation 2-3:

$$h(x,y) = a + bx + cy + \varepsilon(x,y) \qquad \textbf{(Equation 2-3)}$$

where a, b, and c are regression coefficients for the linear drift. The use of a linear drift alone may not be appropriate in the presence of pumped wells and other stresses where local curvature of the potentiometric surface occurs and/or where the aquifer is bounded laterally. In particular, when kriging water levels in the vicinity of pumping wells, rivers, ponds, and trenches, departures from the underlying linear drift are usually evident that correlate with areas of drawdown or mounding that result from discharge or recharge and that illustrate weaknesses in the maps for interpreting groundwater flow directions and rates.

Under these conditions and under certain assumptions, expressions that describe the response of groundwater levels to deterministic forcing functions can be introduced into the mapping as drift terms. Superposition and image theory can enable the incorporation of one or more drift terms and/or one or more hydrologic boundaries within the kriging estimator. In so doing, maps can be prepared that respect the measured data while incorporating independent information about stresses that produce known patterns of response. This is accomplished by supplementing the universal kriging estimator (shown in Equation 2-3) with additional drift terms. Three analytical expressions that are perhaps the most widely applicable are described in the following section.

2.2 Common Analytic Expressions Used as Drift Terms

The drift terms discussed in this section describe changes in groundwater levels in response to three commonly encountered, deterministic stresses have been developed, applied at a variety of sites, and incorporated in the program KT3D_H2O.

2.2.1 Point Sink/Source of Known Strength

The "point sink/source of known strength" drift term is commonly used to represent a pumped groundwater extraction or injection well. This drift term can be derived several ways. When first introduced here, the drift term is derived from the Thiem equation. Later in this document, this drift term will be derived from the Cooper-Jacob equation in order to illustrate the potential impacts of transient conditions that are not considered in the Thiem equation.

The Thiem equation (Equation 2-4) states that pumping at a single well ultimately produce a concentric, logarithmic, pattern of drawdown that is centered on the pumping well (Ferris et al. 1962):

$$s_r = \frac{2.3Q}{2\pi T}\log_{10}\left(\frac{R}{r}\right) \qquad \textbf{(Equation 2-4)}$$

Surfer™ is a trademark of Environmental Systems Research Institute (ESRI), Redlands, California.
Tecplot® is a registered trademark of Tecplot, Inc., Bellevue, Washington.

where (assuming consistent units):

- r = radial distance of the location from the pumped well
- π = pi (3.14159...)
- R = radius of influence of pumping
- Q = pumping rate
- s_r = drawdown at radial distance r due to pumping at rate Q
- T = aquifer transmissivity.

Under certain assumptions, superposition can be used to sum the effect of multiple extracting or injecting wells. The superposition of multiple point sinks/sources can be combined with the linear drift (described in Equation 2-3), as shown in Equation 2-5 ("Kriging Water Levels with a Regional-Linear and Point-Logarithmic Drift" [Tonkin and Larson 2002]; "A Simple Approach to Account for Radial Flow and Boundary Conditions When Kriging Hydraulic Head Fields for Confined Aquifers" [Brochu and Marcotte 2003]):

$$h(x,y) = a + bx + cy + d\sum_{1}^{m} Q_i(r) + \varepsilon(x,y) \quad \textbf{(Equation 2-5)}$$

where:

- d = regression coefficient pertaining to the point sink/source drift term
- $\sum_{1}^{m}$ = summation from 1 to m, where m is the number of point sink/sources
- $Q_i(r)$ = "drawdown or mounding factor" due to the i^{th} sink/source at distance r.

Equipotentials approaching a point sink or source are concentric about that point, in the absence of any other influences or trends. They are circular and analogous to patterns of drawdown or mounding in response to extraction or injection.

2.2.2 Line Sink/Source of Known Strength

The "line sink/source of known strength" drift term is commonly used to represent mounding or drawdown of the water table in response to features such as infiltration galleries or interception trenches. When used in mapping, the line sink/source can also be used under some circumstances to depict river boundaries. The complex potential representing a line sink/source of known strength is shown in Equations 2-6 and 2-7 (*Groundwater Mechanics* [Strack 1989]):

$$\Omega = \frac{\sigma L}{4\pi}\left((Z+1)Ln(Z+1) - (Z-1)Ln(Z-1)\right) \quad \textbf{(Equation 2-6)}$$

$$Z = \frac{2z - (z1 + z2)}{(z2 - z1)} \quad \textbf{(Equation 2-7)}$$

where (assuming consistent units):

- σL = discharge per-unit-length
- Ω = complex discharge potential
- Z = dimension-less complex variable (Strack 1989)
- z1 = complex ordinate of one end of the line sink/source
- z2 = complex ordinate of the other end of the line sink/source
- z = $x + iy$ is the point where Z and Ω are evaluated.

Since σL (the discharge per unit length) is assumed to be constant (although unknown), the solution for Ω is linear and can be obtained through the universal kriging equations. The superposition of multiple line sinks/sources can be combined with the linear drift and the point sink/source drift (Equation 2-8) as follows:

$$h(x,y) = a + bx + cy + d\sum_{1}^{m} Q_i(r) + e\sum_{1}^{n} L_i(r) + \varepsilon(x,y) \qquad \textbf{(Equation 2-8)}$$

where:

- e = regression coefficient pertaining to the line sink/source drift term
- $\sum_{1}^{n}$ = summation from 1 to n where n = the number of line sink/sources
- $L_i(r)$ = "drawdown or mounding factor" due to the i^{th} line sink/source at distance, r.

The line sink/source is derived by integrating a line of point sink/sources (Strack 1989). Equipotentials approaching a finite-length line sink/source are approximately parallel to that feature; however, finite-length features exhibit curved equipotentials at each end. In the far field, the finite-length line sink/source produces concentric equipotentials that converge asymptotically to those produced by a point sink/source of the same total strength (i.e., discharge or recharge rate).

2.2.3 Circular Source of Known Strength

The "circular source of known strength" drift term is commonly used to represent the response of the unconfined water table to recharge from a circular pond or perched basin. Mounding in response to infiltration from a circular feature is shown in Equations 2-9 and 2-10 (Strack 1989):

For $(0 \le r_j \le R_j)$ **(Equation 2-9)**

$$\mathrm{G}(\mathrm{x}, \mathrm{y}, \mathrm{x}_j, \mathrm{y}_j, \mathrm{R}_j) = -\frac{1}{4}\left[(x-x_j)^2 + (y-y_j)^2 + R_j^{\,2}\right]$$

For $(R_j \le r_j < \infty)$ **(Equation 2-10)**

$$\mathrm{G}(\mathrm{x}, \mathrm{y}, \mathrm{x}_j, \mathrm{y}_j, \mathrm{R}) = -\frac{R_j^{\,2}}{4} Ln \frac{(x-x_j)^2 + (y-y_j)^2}{R_j^{\,2}}$$

where (assuming consistent units):

x_j, y_j = ordinates of the center of the j^{th} circular source

r_j = radius of point (x,y) from the center of the j^{th} circular source

R_j = radius of the j^{th} circular source

∞ = infinity.

Strictly, this element cannot be used to represent a penetrating (gaining) circular pit or large-diameter well because the head within such a feature would be uniform rather than variable (as described in Equation 2-9). However, if the feature is relatively small and/or the background gradient within the aquifer (described by the second and third terms of Equation 2-8) is relatively low, then a close approximation to a penetrating (gaining) circular pit or large-diameter well can be obtained by setting

$$G = \frac{R_j^2}{4} for\ (0 \leq r_j \leq R_j)$$

in Equation 2-9.

The superposition of multiple circular sources can be combined with the linear drift, the point sink/source drift, and the line sink/source drift (described by Equation 2-8), resulting in the following (Equation 2-11) as a basis for mapping measured water-level data:

$$h(x,y) = a + bx + cy + d\sum_1^m Q_i(r) + e\sum_1^n L_i(r) + f\sum_1^o P_i(r) + \varepsilon(x,y) \qquad \textbf{(Equation 2-11)}$$

where:

f = regression coefficient pertaining to the circular source drift term

$\sum_1^o$ = summation from 1 to o, where o is the number of circular sources

$P_i(r)$ = "drawdown or mounding factor" due to the i^{th} circular source at distance r.

2.2.4 Summary

The expressions described by Equation 2-4 for the point sink/source, Equations 2-6 and 2-7 for the line sink/source, and Equations 2-9 and 2-10 for the circular source contain variables that might typically be assumed constant for a given mapping problem (e.g., transmissivity) and variables that are known to change depending on the component of the drift term. For example, the extraction rate may differ at each pumped well, and the radius (r_i) will change depending on the ordinates (x,y) of the node at which the kriging estimate is required. In formulating Equations 2-5, 2-8, and 2-11, the variables that are constant for each drift term lie outside of the summation, while variables that can change for each drift term lie inside the summation. Tonkin and Larson (2002) and Brochu and Marcotte (2003) describe how the universal kriging method might be used to infer bulk aquifer properties from the coefficients obtained by fitting Equation 2-5, 2-8, or 2-11 to the measured data. However, this document focuses on the preparation of maps rather than on this potential role in estimating bulk aquifer properties.

Finally, Equation 2-11 depicts the grouping of like stresses within a single drift term. For example, according to Equation 2-11, all line sinks/sources are grouped within a single term:

$$(e\sum_1^n L(r_i)).$$

However, this is short-hand notation and not a limitation of the method, which allows similar drift terms to be grouped quite arbitrarily, enabling the experienced hydrogeologist to incorporate his/her understanding of the conceptual site model in the drift term definition. For example, separate drift terms may be specified for two line sinks that are believed to exhibit different per-unit-length exchange rates with the groundwater system, or separate drift terms may be specified for two wells that are believed to be screened within aquifer units that exhibit different transmissivities and for which it would be appropriate to obtain different regression coefficients.

2.3 Lateral Boundaries

The following discussion focuses on point sinks/sources, but it applies equally to the linear and circular elements described above.

The presence of impermeable (no-flow) or zero-drawdown (constant-head) lateral boundaries violates one of the key assumptions underlying the analytical expressions described above (i.e., that the aquifer in question is of infinite areal extent). The method of images can be used to represent the effect of certain relatively simple boundaries. In the case of point sinks/sources, this is accomplished through the specification of imaginary, or image point sinks/sources, that reproduce the effect of the boundary(ies) within the mapped domain (Ferris et al. 1962; "The Principal of Superposition and Its Application in Ground-Water Hydraulics" [Reilly et al. 1987]; Strack 1989). For example, for a single extraction well pumping in an aquifer bounded on one side by an impermeable (i.e., no-flow) boundary, the effect of the boundary is mimicked using a single image well located outside of the aquifer, equidistant from the impermeable boundary, which possesses an analogous strength (discharge rate) to the true extraction well. The same general approach is true for the linear and circular elements.

Defining the location(s) and rate(s) for multiple elements to represent the effects of a single impermeable or zero-drawdown boundary is straightforward. This can also be easily extended to two parallel boundaries. Ferris et al. (1962) illustrate that in the presence of parallel boundaries, the effect of each image well that is added to compensate for the first boundary must be compensated for by adding complementary image wells in the second boundary. This compensation continues ad infinitum, forming an asymptotic series. The apparent convergence of this series is problem-specific (i.e., it can depend on the number and strength of the stress[es], the proximity of the boundaries, the purpose of the mapping, and the accuracy that is required). Regardless, manual calculation of an image well series beyond the first image set can be tedious, and using a program to calculate the reflection matrix for parallel boundaries and determine a specified number of image sets is most appropriate.

The application of image theory is complex in the presence of multiple boundaries, particularly if these boundaries are of mixed type (i.e., impermeable and zero-drawdown boundaries) and/or are not parallel (Reilly et al. 1987).

2.4 Regional Hydraulic Gradient

Accurate estimates of the background or regional hydraulic gradient are important where independent methods (e.g., the relationships presented in Section 4.3) will be used to estimate or verify the extent of capture, where compliance objectives for the remedy include restrictions on wider area gradient changes, and/or when using water-level maps to define the lateral boundaries of a numerical groundwater flow model.

Tonkin and Larson (2002) use a synthetic example to illustrate that in the presence of singularities (e.g., pumped wells), kriging using a linear drift (as described by Equation 2-3), may calculate an erroneous background or regional hydraulic gradient that is biased by the (justifiable) preferential location of monitoring wells near the pumped wells. Tonkin and Larson (2002) suggest that including appropriate drift terms can improve the estimate of the background hydraulic gradient. They show that on such occasions, the surface obtained using a linear drift is "muted," while use of the appropriate drift(s) produces the characteristic curvature approaching pumped wells while converging asymptotically on the background gradient at some distance from the drift(s) (Figures 2-1 and 2-2). In the ideal hypothetical example, the coefficients of the fitted linear drift obtained using Equations 2-3 and 2-5 differed considerably, and the trend coefficients (b and c) obtained using Equation 2-3 were about one-half of the true (in that case, known) coefficients.

2.5 Assumptions and Limitations

Appendix A describes verifications of the method implementation for each of the analytic expressions included in Equation 2-11. The discussion in Appendix A demonstrates that under ideal circumstances, incorporating these drift terms within universal kriging can accurately reproduce the potentiometric surface. However, ideal circumstances are rarely encountered and, as a result, the use of the mapping methods requires an understanding of the assumptions and limitations that are described in the following sections.

2.5.1 Assumptions

2.5.1.1 Point Sink/Source of Known Strength

Since the point sink/source can be derived from the Thiem or Cooper-Jacob equations, the assumptions that are common to these equations are implicit in the mapping technique, principally as follows (*Engineering Hydraulics: Proceedings of Fourth Hydraulics Conference* [Rouse 1949]):

- The aquifer is homogeneous, isotropic, and of infinite areal extent.
- The aquifer is confined so the transmissivity is uniform and unchanging. If the aquifer is unconfined, drawdowns should be a reasonably small fraction of the aquifer saturated thickness.
- The pumping well penetrates and receives water from the entire saturated thickness of the aquifer (i.e., the well is not partially penetrating).

In addition to these common assumptions, the following assumption, applicable to the Theim equation alone, applies:

- The drawdown and/or mounding has/have reached a (quasi-) steady-state condition. If this is not the case, the rate of change in hydraulic gradients should approach zero.

With regard partially penetrating wells, "Variations in Capture Zone Geometry of Partially Penetrating Wells in Unconfined Aquifers" (Bair and Lahm 1996) presents empirical evaluation of the effect of partial penetration on capture zone dimensions, while "Hydrodynamics of the Capture Zone of a Partially Penetrating Well in a Confined Aquifer" (Faybishenko et al. 1995), "Determining 3D Capture Zones in Homogeneous, Anisotropic Aquifers" (Schafer 1996), and *Analytic Element Modeling of Ground-Water Flow and High Performance Computing* (EPA/600/S-00/001) describe the geometry of capture zones developed by partially penetrating wells. While not directly applicable to water-level mapping, these studies provide indication of the likely impact of partial penetration on estimating capture zones.

With regard to the final assumption (i.e., the attainment of [quasi-] steady-state conditions), it is instructive to examine the Cooper-Jacob equation to assess when and to what degree this assumption may affect the water-level mapping technique.

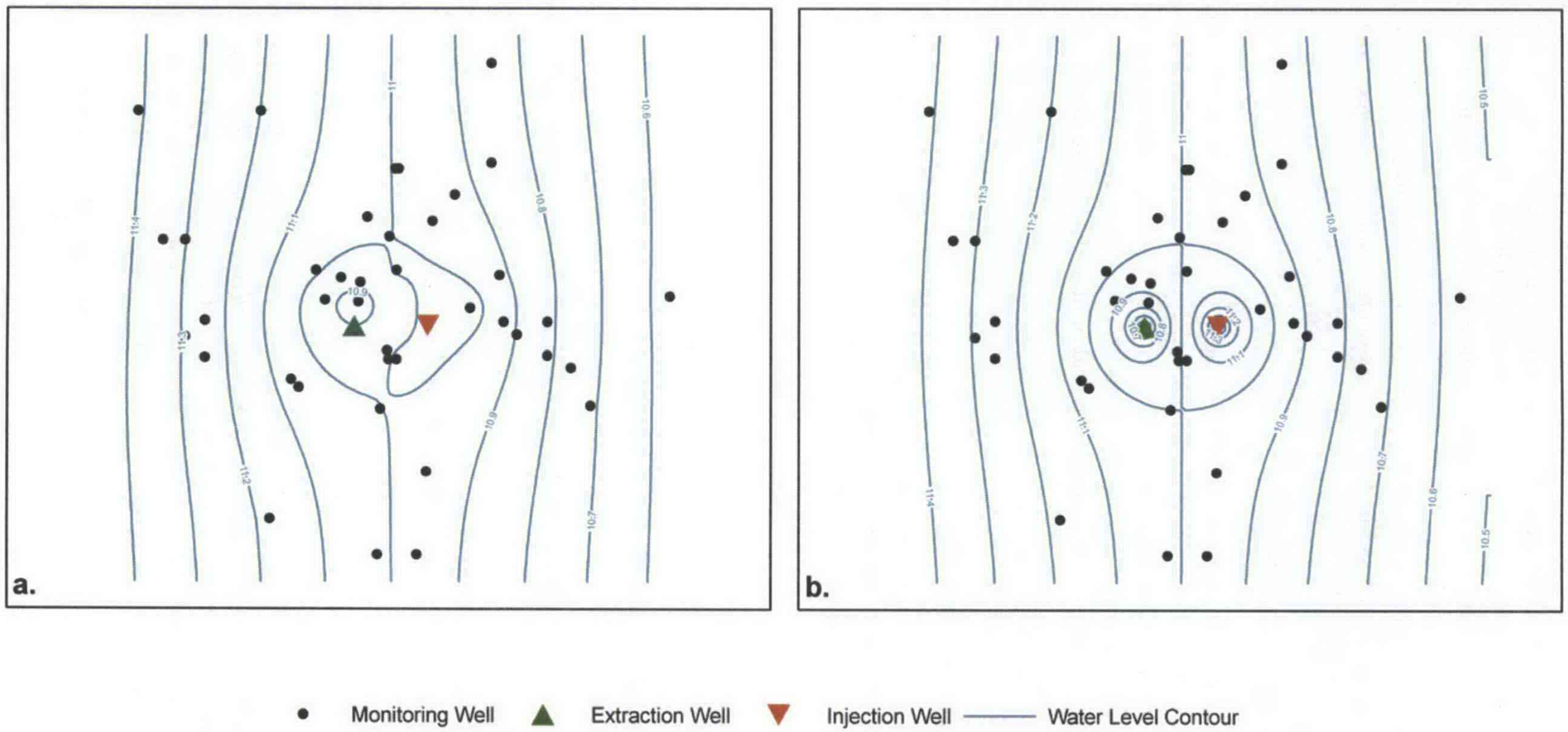

Figure 2-1. Plan View of Synthetic Water-Level Surface Mapped (a) Without and (b) Without Appropriate Drift Terms

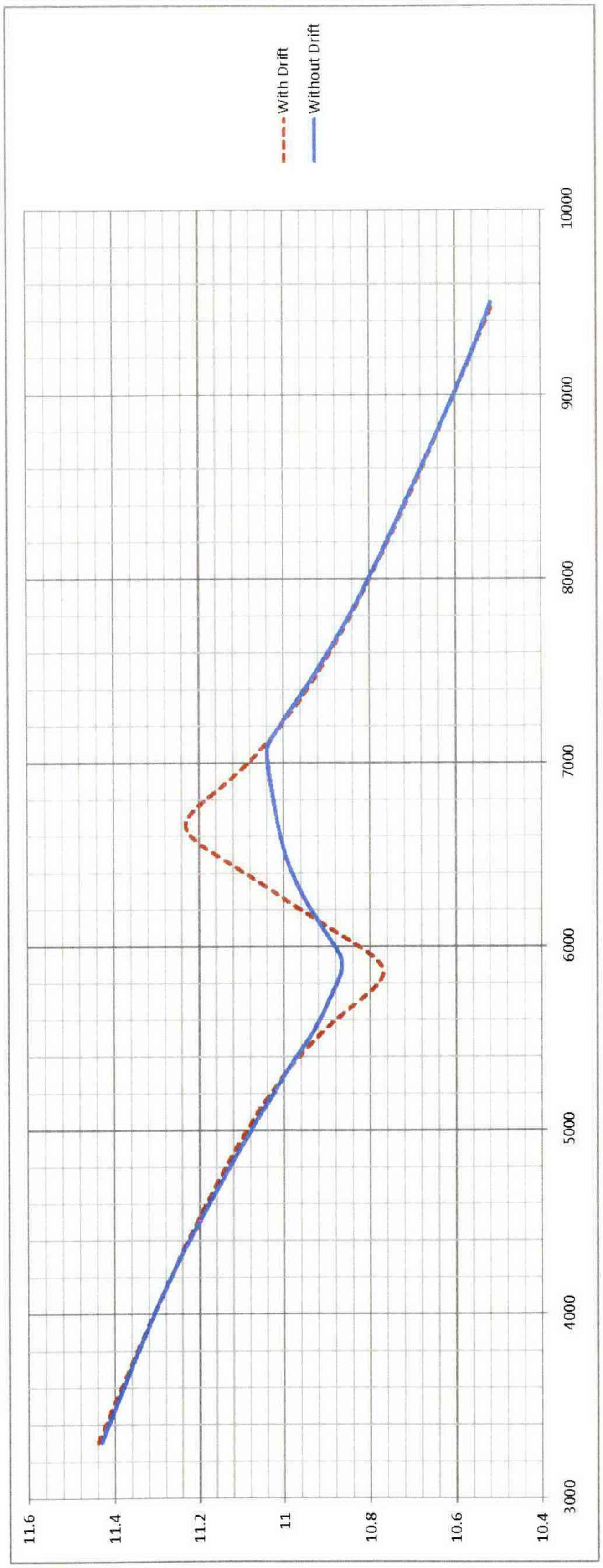

Figure 2-2. Section View of Synthetic Water-Level Surface Mapped Without and with Appropriate Drift Terms

The Cooper-Jacob equation is often illustrated as shown in Equation 2-13:

$$s_r = \frac{Q}{4\pi T}\ln\left(\frac{2.25Tt}{r^2 S}\right) \qquad \textbf{(Equation 2-13)}$$

Equation 2-13 can also be presented as shown in Equation 2-14:

$$s_r = \frac{Q}{4\pi T}\left(\ln\left(\frac{2.25Tt}{S}\right) + \ln\left(\frac{1}{r^2}\right)\right) \qquad \textbf{(Equation 2-14)}$$

Using the rule of logarithms, the second term in parenthesis in Equation 2-14 can also be illustrated as *-2ln(r)* (i.e., negative 2 times the logarithm of the separation distance). The first term in parenthesis in Equation 2-14 is a function of the logarithm of time (transmissivity and the reciprocal of storage) and is independent of the distance from the pumped well. The second term in parenthesis in the equation is solely a function of the logarithm of distance from the pumped well (which is consistent with Equation 2-4).

Under the assumption that all pumped wells commenced operations simultaneously, at any time, *t* (the first term in parenthesis in Equation 2-14), applies equally throughout the mapped area as a vertical offset. Since the drift described by Equation 2-11 is assumed to apply to the entire data set (i.e., local data neighborhoods are not typically used with universal kriging), the regression coefficients of Equation 2-11 are calculated from a global estimation of *h(x,y)*. As such, the vertical offset described by the first term of Equation 2-14 is subsumed within the regression coefficient (*a*) of Equation 2-11. This suggests that the mapping technique may produce reasonable depictions of the potentiometric surface relatively soon after the start of pumping (consistent with the assumptions of the Cooper-Jacob equation) and from that time forward, if the remaining assumptions are reasonably adhered to. An empirical evaluation of this assumption is also presented in Appendix B.

2.5.1.2 Line Sink/Source of Known Strength

The line sink/source is derived by integrating a line of point sinks/sources within a system that exhibits Dupuit-Forshheimer flow (Strack 1989). The assumptions that underlie the Thiem equation are implicit in the use of this drift term within the mapping technique, as described for the point sink/source. In keeping with the conditions encountered within unconfined aquifers, Dupuit-Forschheimer flow does not necessarily assume a constant transmissivity (*Analytic Element of Modeling of Groundwater Flow* [Haitjema 1995]). However, the effect of changing transmissivity is typically negligible, as long as the saturated thickness does not change substantially ("Hydraulics of Wells" [Hantush 1964]).

2.5.1.3 Circular Source of Known Strength

Use of the circular source drift term assumes local infiltration of water and shallow, unconfined flow rather than confined flow (as is assumed for the point sink/source). Consistent with the Dupuit-Forschheimer assumption, it is assumed that vertical components of flow are negligible. As a result, the assumptions underlying the use of the circular source are essentially analogous to the assumptions underlying use of the point sink/source. Consistent with the line sink/source of known strength, the effect of changing transmissivity is typically negligible, as long as the saturated thickness does not change substantially (Hantush 1964).

2.5.2 Limitations

In general terms, the closer that the conditions encountered at the site adhere to the assumptions listed above (i.e., the more ideal the site), the more reliable the results obtained using the mapping method described. This can be considered qualitatively in the context of two end-member sites. Typically the conditions encountered at real-world sites will lie somewhere between these end members.

At the first site, the aquifer is unconfined and the pumped wells in question penetrate the full saturated thickness of the aquifer. The hydraulic conductivity is relatively homogeneous and isotropic, and the distribution of monitoring wells at which water levels are recorded is relatively dense. Under these circumstances, the combination of the close adherence to the underlying assumptions and the control provided by the large number of monitoring wells leads to maps that accurately depict groundwater flow directions and rates, as well as the extents of capture. For this end member, the methods described certainly offer an alternative to (or could supplement) the use of a numerical model for inferring the extent of capture. This is particularly the case because a large number of water-level data sets can be mapped relatively easily and rapidly using the methods described (see Section 3.2).

At the second site, the aquifer is unconfined and receives substantial distributed recharge. The pumped wells in question penetrate a small fraction of the full saturated thickness of the aquifer, and drawdown is a relatively large fraction of this thickness. The hydraulic conductivity is very heterogeneous and anisotropic, and there is a small number of monitoring wells where water levels are recorded. Under these circumstances, the combination of the violations of the underlying assumptions and the lack of control provided by the small number of monitoring wells, leads to maps that may not accurately depict groundwater flow directions and rates, as well as the extents of capture. To mitigate this, it may be appropriate to increase the density of monitoring in key locations.

2.5.3 Mapping Versus Modeling

For the more complex end member described above, it is reasonable to ask, "What is the best approach to estimating capture?" While the use of the water-level mapping technique is compromised by violations of the underlying assumptions described earlier, the application of a numerical model to explicitly simulate the detailed characteristics of the system may require sophisticated codes and methods, a high level of expertise, and rigorous calibration, without a guarantee of predictive accuracy (e.g., "The Role of Quantitative Models in Science" [Oreskes 2003]; "Risk Analysis: The Unbearable Cleverness of Bluffing" [Klemes 2002]; and "Role of the Calibration Process in Reducing Model Predictive Error" [Moore and Doherty 2005]). In the case of relatively complex systems such as this, it is advisable to use multiple lines of evidence to infer the extent of capture (EPA 600/R-08/003). In many cases, the primary lines of evidence will comprise numerical modeling and water-level mapping, supplemented by calculations such as those presented in Section 4.3.

There is no doubt that numerical models possess a wide range of potential application beyond capture zone analysis. Furthermore, under all circumstances, some forms of predictive modeling (whether simple or sophisticated) must be used during remedy design to understand how the groundwater may respond to pumping. Once the remedy is operating and suitable measurement data are available, more empirical methods (e.g., the mapping technique) may be used to infer if these predictions were accurate.

Table 2-1 lists some of the advantages and disadvantages of using numerical groundwater flow modeling together with particle tracking, versus using water-level mapping and particle-tracking methods described above solely for purposes of inferring the extent of capture by pump-and-treat systems.

Table 2-1. Some Advantages and Disadvantages of Numerical Modeling and Water-Level Mapping When Evaluating Hydraulic Capture

Modeling		Mapping	
Advantages	Disadvantages	Advantages	Disadvantages
Complex geometries, including fully three-dimensional systems, explicitly represented.	Simulation of complex geometries leads to a highly parameterized problem.	Transient analysis is implicit in capture frequency map.	Complex geometries are implicit but can be difficult to consider explicitly.
Mass-conservative reactive transport can be completed.	Requires definition of lateral boundary conditions.	Requirement for velocity knowledge mitigated by capture frequency map.	Presently limited to layered two-dimensional approach.
Model serves as basis for predictive "what-if" scenarios.	Evaluation of new data can require model recalibration.	Evaluating new data sets is straight forward due to built-in regression (calibration).	Only limited predictive "what-if" scenarios are possible.
	Steady-state analysis assumes transients insignificant.	A priori definition of lateral boundary conditions generally is not required.	Complex lateral or internal boundaries, if required, can be cumbersome.
	Transient analysis requires calibration and knowledge of velocities.		Mass-conservative reactive transport approximated using advective-dispersive particle tracking.

For example, the mapping method reproduces measured water levels while not requiring many of the inputs required for numerical models. As a result, once the universal kriging settings are defined, any number of water-level data sets can be mapped and evaluated without the intensive recalibration required by numerical models. However, the mapping method assumes that flow is dominantly horizontal (vertical components of flow are negligible) and, as such, may not be applicable in some complex three-dimensional settings.

It is therefore suggested that water-level mapping and numerical modeling should be considered complementary, as follows:

- At sites where the construction of a numerical model may be difficult, yet the mapping method appears suitable, the mapping method may provide a primary line of evidence and may offer an alternative to the use of a groundwater flow model.
- At sites where a suitable model exists or can be constructed, the mapping method may supplement the use of the groundwater flow model, if the underlying assumptions are not grossly violated.

2.6 Summary

The discussion in this chapter describes a technique for interpolating water-level data that was developed to assist (not replace) the experienced hydrogeologist in preparing maps of groundwater levels in the presence of deterministic stresses, such as pumped wells. To date, some combination of the drift terms described above has sufficed to prepare water-level maps at most sites; however, additional drift terms could be incorporated into the method. For example, the KT3D program (Deutsch and Journal 1992) includes quadratic drift terms that may be suitable for representing the curvature of the potentiometric surface in some unconfined aquifers and/or in response to distributed recharge. Under most practical circumstances, using the methods described can improve the interpretation of measured water-level data and corresponding flow directions and rates, versus that which can be achieved using more common automated techniques. This generally leads to less subjective interpretations than those obtained through hand-contouring.

From a qualitative standpoint, the preparation of water-level maps alone may be sufficient for many sites and applications. However, Chapter 3 describes how water-level maps prepared using the techniques described above may be used to estimate the extent of hydraulic capture developed by one or more extraction wells.

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3 Estimating the Extent of Capture

This chapter discusses the use of particle tracking to estimate the extent of capture and describes the capture frequency map (CFM), which is a method for visually depicting the results of numerous capture zone analyses.

3.1 Instantaneous Capture Using Particle Tracking

The principal output from the interpolation of measured water-level data is usually a two-dimensional grid of approximate groundwater elevations that is suitable for contouring to visualize general flow patterns. However, when the method described in Chapter 2 (or another suitable technique) is used to generate a map of groundwater elevations, the resulting surface may be suitable for particle tracking to depict approximate advective(-dispersive) transport, estimate groundwater flow directions, and approximate the extent of capture. By recording the fate of each tracked particle, the approximate extent of capture developed by one or more extraction wells can be depicted. The program KT3D_H2O produces output files that enable the depiction of water levels, capture zones, and CFMs in Surfer and ArcGIS®/ArcMAP®, as well as other programs.

3.1.1 Far-Field Particle Tracking

To depict flow directions and rates and to estimate capture, particles are released from locations distributed throughout the mapped area. At any point in the mapped area, the gradient, or slope *i* of the mapped surface can be determined using finite differences. This slope can be combined with approximate values for the hydraulic conductivity (K) and effective porosity (n_e) to estimate the velocity, $V(x,y)$, using Equation 3-1:

$$V(x,y) = Ki / n_e \qquad \textbf{(Equation 3-1)}$$

The particle's movement can then be integrated and its ultimate fate (including capture at a well) can be recorded.

In the KT3D_H2O program, particle tracking is accomplished using the fourth-order Runge-Kutta (RK4) numerical integration scheme (*Numerical Recipes in Fortran-90* [Press et al. 1992]). This tracking approach is based upon that implemented in the program Path3D (*PATH3D: A Groundwater Path and Travel-Time Simulator, Version 3.*0 [Zheng 1992]), which has been demonstrated to provide very similar results to the U.S. Geological Survey particle-tracking program MODPATH (*User's Guide for MODPATH/MODPATH-PLOT, Version 3: A Particle Tracking Post-Processing Package for MODFLOW, the U.S. Geological Survey Finite-Difference Ground-Water Flow Model* [Pollock 1994]) when used with MODFLOW ("A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model" [MacDonald and Harbaugh 1988]). Particle tracking using the RK4 approach indicates the approximate path of migrating groundwater and contaminants, as well as the (relative) timing of the arrival of contaminants at points of interest.

3.1.2 Near-Field Particle Tracking

The use of local finite differences to calculate the gradient that is necessary to track particles using the RK4 scheme is reliable in areas where gradients are relatively uniform. However, in the vicinity of pumped wells and other stresses, the local finite difference approximation to the curvature of the potentiometric surface can be prone to error, despite the use of the high-order RK4 scheme. Detailed

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ArcGIS® and ArcMAP® are registered trademarks of Environmental Systems Research Institute (ESRI), Redlands, California analysis of the effects of grid discretization on estimation of capture is not presented here. In general terms, some of these might be similar to the effects that arise in two-dimensional, finite-difference groundwater models, as described in "Analysis of Particle Tracking Errors Associated with Spatial Discretization" (Zheng 1994).

To mitigate the impact of these grid-dependent, near-field errors in particle tracking and in estimates of capture, the particle-tracking routine distributed with the KT3D_H2O program uses a local regression (based on Equation 2-5) to calculate a more reasonable representation of the curved velocity field near pumping wells. When a tracked particle enters a region of nodes that encompass one or more pumped wells, gradients are obtained by estimating the head value at three locations (which is necessary to obtain gradients in the *x* and *y* ordinate directions), using Equation 2-5 together with the water levels at the surrounding nodes and the pumping rates at nearby wells. This approach has the following advantages:

- The velocity field converges on the well (Figure 3-1) rather than an arbitrary interpolation grid point, which produces more reasonable capture zones than those calculated when interpolation on the basis of widely spaced nodes is used to estimate gradients (Figure 3-2).
- Initial water-level maps and capture zones can be prepared using relatively coarse grids, with some confidence that the capture zones will be similar to those obtained using finer grids. (It is recommended, however, that final maps be prepared using a fine calculation grid.)

A similar approach could be implemented for both the line sink/source and circular source.

3.1.3 Calculated Capture Zones

Applications of the particle-tracking technique indicate that the method can provide reasonable estimates of system-wide capture within the footprint of the measured data, under the circumstances that the extent drawdown due to pumping is reflected in the measured water levels. As described below, the method can also be used to combine a large number of monitoring events within a single "ensemble" depiction of capture referred to as a CFM. However, since the mapping method does not necessarily conserve flow (unlike a numerical model, for which mass conservation is explicit), distinguishing the capture zones of individual wells within a complex well field can sometimes be difficult. Therefore, it is recommended that inferences based on the mapping method primarily focus on the remedy-wide extent of capture and secondarily consider the extents of individual well capture zones.

To perform particle tracking, values are required for the effective (mobile) porosity and for the hydraulic conductivity. Under most circumstances, the values that are provided do not alter the calculated capture zones (although the values provided can alter the time required to complete the calculations) since tracking is completed independently on each mapped surface. However, if time-of-travel zones are calculated, and/or if transient tracking is undertaken, the results depend on the values provided for effective porosity and hydraulic conductivity. In the case of transient tracking, one or more particles is tracked for a defined time period (e.g., 7 days in the case that weekly water-level maps have been prepared) on each mapped surface and the fate of each particle integrated over time. This capability is provided with the KT3D_H2O program and is typically used when evaluating the historic migration of contaminants rather than the extent of capture.

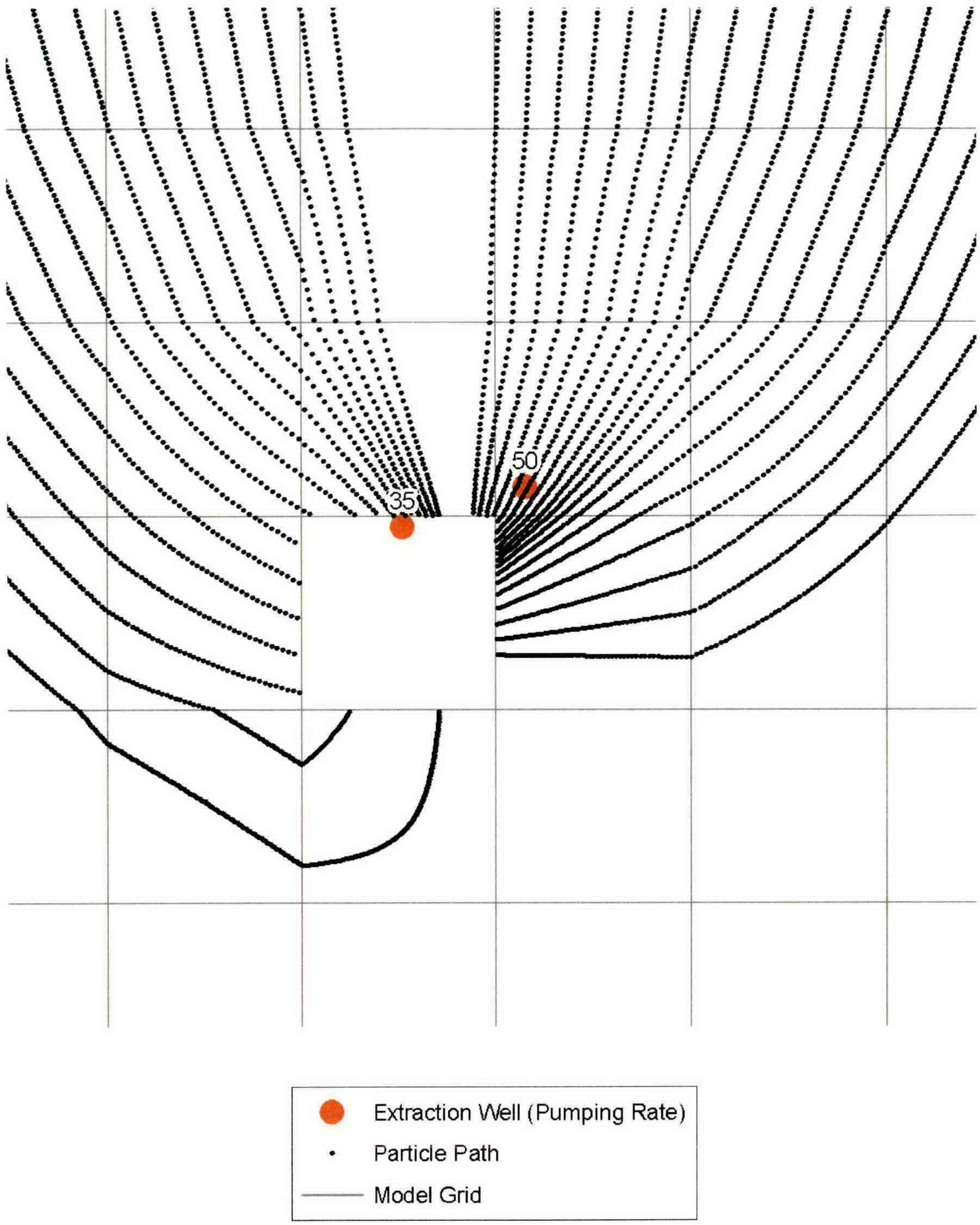

Figure 3-1. Particle Paths in the Vicinity of a Pumped Well Calculated Without Incorporation of the Point Sink Drift Term Within Particle Tracking

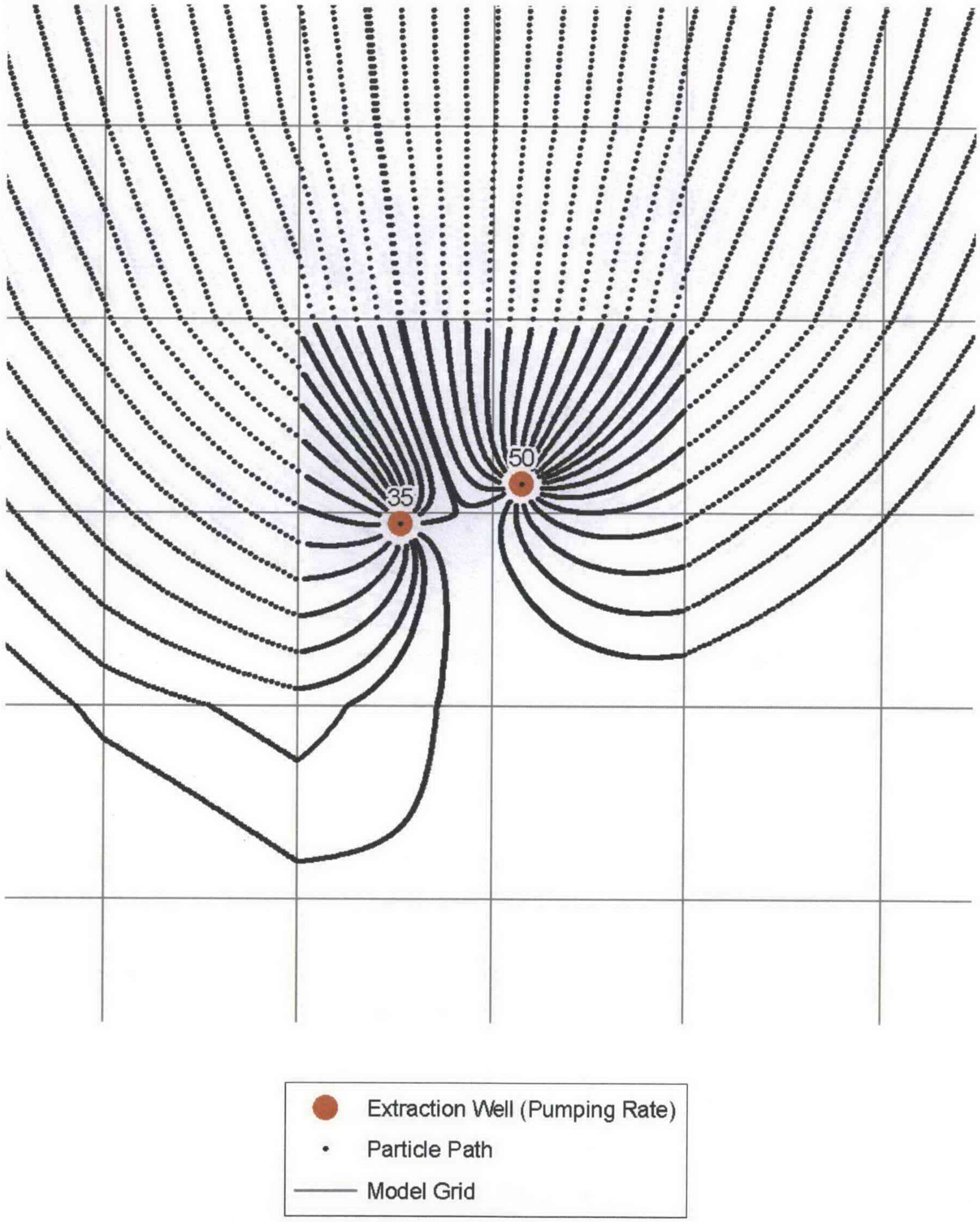

Figure 3-2. Particle Paths in the Vicinity of a Pumped Well Calculated With Incorporation of the Point Sink Drift Term Within Particle Tracking

3.2 Capture Frequency Map

At many sites, numerous water-level data sets are available due to regular measurements obtained using electronic tapes and other manual methods, and/or as a result of the instrumentation of wells with pressure transducers and data loggers. In these instances, maps can be produced that depict approximate water levels and capture zones for each monitoring event, or for each interval at which the data loggers record water levels. However, discerning a "best estimate" of capture on the basis of tens or hundreds of individual capture maps can be very difficult, and the CFM was developed to accomplish this.

The CFM is a single map that depicts the capture calculated from multiple monitoring events. It depicts the frequency with which a particle released within the mapped domain terminates at a pumped well, calculated over all mapped events. A frequency of 1.0 indicates that the particle is captured on every map produced, a frequency of 0.0 (zero) indicates that a particle is not captured on any of the maps, and intermediate frequencies indicate that the particle is captured using some of the maps and not others (Figure 3-3).

There are many potential causes for capture frequencies that range between zero and 1.0, including changing pumping rates; seasonal patterns (e.g., changing river stages); errors accompanying water-level measurements; and, under some circumstances, the effects of violations of the underlying assumptions. As a result, the inference from a CFM typically focuses on the location and extent of the higher capture frequencies, and also on the relative distribution and extents of the low and high capture frequencies. This is discussed further in Appendix B.

Maps of capture frequency are most meaningful if the pump-and-treat remedy has operated essentially continuously (even if at varying rates) for a defined period of time. A CFM can be misleading if it is calculated for a relatively long period during which the remedy was inoperative for a substantial period of time. For example, at a site at which a remedy operates for 3 months of the year at a constant rate within an ideal aquifer, a CFM would suggest that the capture frequency is 25 percent throughout the year, whereas the correct interpretation is that the capture frequency is 100 percent during periods of operation and is zero during periods of non-operation.

When calculating a CFM, particle tracking is conducted independently on each mapped surface until the fate of each particle is determined. As a result, capture frequency is not analogous to capture efficiency, as described in "The Capture Efficiency Map: The Capture Zone Under Time-Varying Flow" (Festger and Walter 2002), which used particle tracking with a transient groundwater model. However, applications of the method to synthetic data sets (see Appendix B) and field data suggest that CFMs may empirically reflect the transient development of hydraulic capture.

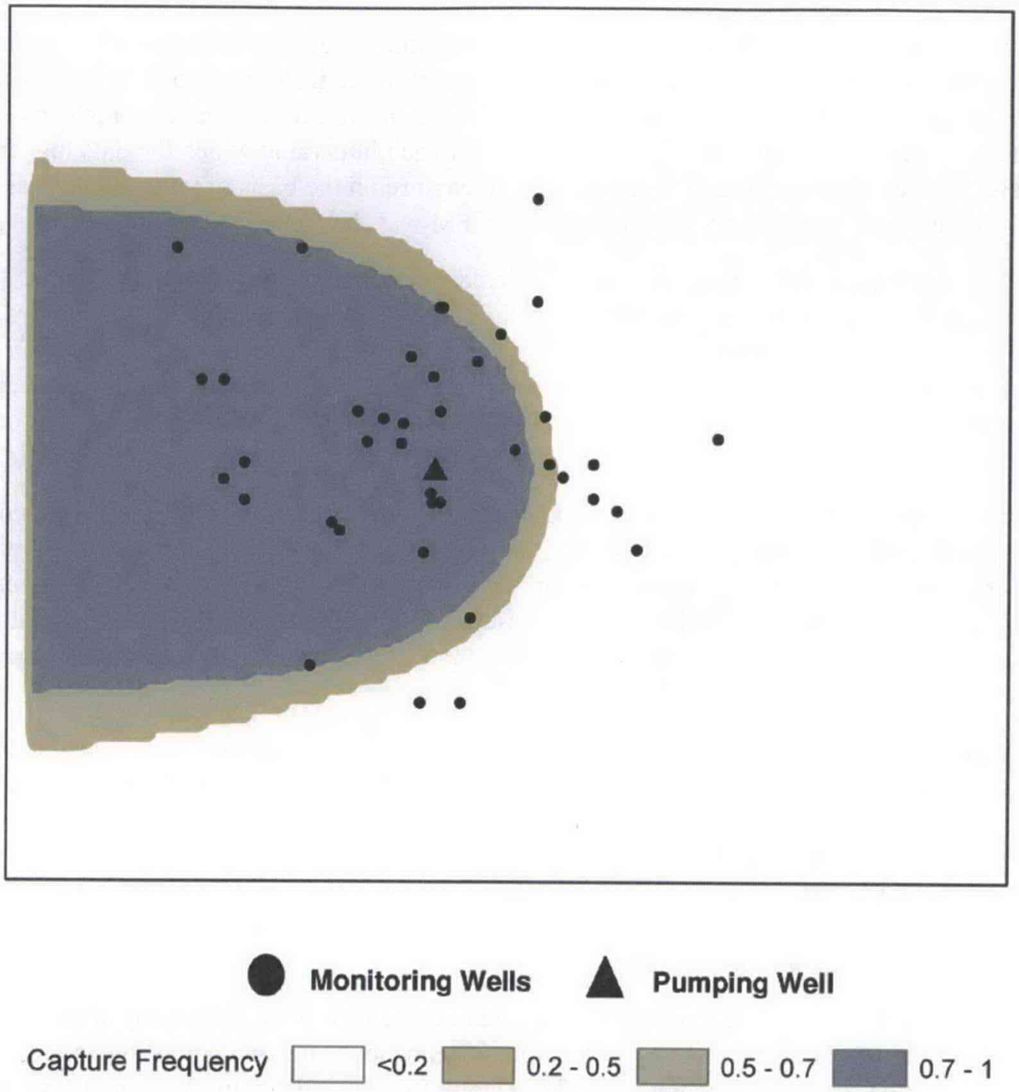

Figure 3-3. Example Capture Frequency Map for Time-Varying Pumping from an Aquifer Exhibiting Steady Uniform Flow Prior to Pumping

4 Recommendations for Implementation

This chapter provides general guidelines on implementing the methods described herein. The guidelines are based on previous applications and are not prescriptive. Although the methods described can improve the inference possible from water-level maps, care must be used during implementation. Because each site is different, different implementation is suitable at different sites. It is therefore recommend that an experienced hydrogeologist with intimate knowledge of the site use the method to prepare maps, which is the best way to obtain water-level depictions that lead to reasonable interpretations of remedy performance.

4.1 Water-Level Mapping

4.1.1 Data Requirements and Quality Control

The essential data requirements for implementing the methods described are as follows:

- Groundwater levels at monitoring wells and, under some circumstances, at extraction and injection wells (see discussion below)
- Location(s) and rate(s) of groundwater extraction and/or injection
- Geographic location and geometry of other sources/sinks to groundwater
- Presence, type, and likely impact of lateral hydrologic boundaries
- Information that might be used to collect subsets of the various deterministic stresses into different drift terms.

Although this list is relatively small, the following items should be considered when obtaining and processing data for mapping, in addition to more site-specific considerations (the list that follows is not exhaustive):

- Vertical and horizontal reference data and units must be consistent. Errors in these data can introduce artificial "peaks" and "valleys," as well as gradients within the water-level data, which will impart error in the maps.
- Extraction and injection rates must be in consistent units. When sets of wells are collected in to different drift terms, this requirement can sometimes be relaxed; however, it remains good practice to use consistent units.
- Water-level data should be thoroughly reviewed for inconsistencies, including the following:
  - Transcription errors, which are commonly identified by plotting hydrographs
  - Disagreement between manual and automated water levels, such as created by pressure transducer drift.
- Pumping data should be thoroughly reviewed for inconsistencies, such as follows:
  - Large disagreements between the sum(s) of individual well pumping rates and totalized rates (e.g., those recorded at a treatment plant)
  - Discrepancies between total extraction and total injection rates in closed systems (i.e., lack of mass balance).

- Information on screened intervals of pumping and monitoring well should be evaluated to identify pumped wells that may only partially penetrate the aquifer and monitoring wells with water levels that may be measurably impacted by this partial penetration.

Perhaps most importantly, it is vital that approximate (although essentially relative) pumping rates are known for each occasion on which the water levels will be mapped (i.e., the remedy must be operating). The use of Equations 2-5, 2-8, and/or 2-11 for mapping is predicated on knowledge of the extraction and injection rates. If the mapping is performed at a time when these rates are not known or if the system was not operating, the results may be nonsensical.

It is stated above that "relative" pumping rates are required, in contradistinction to absolute rates. As described in Section 2.2.4 in formulating Equations 2-5, 2-8, and 2-11, variables that are constant for each drift term lie outside of the summations, while variables that can change for each drift term lie inside the summation. The (linear) coefficients for each drift term are estimated through the solution of the universal kriging system of equations. As a result, as long as pumping rates are known within a constant multiplier, the map that results from the use of Equation 2-5, 2-8, and/or 2-11 will be unaffected (although the values estimated for the drift term coefficients, and any inference based on these, would be affected). Nevertheless, it is good practice to use consistent dimensions and units, as well as accurate input data, when preparing maps.

4.1.2 Water Levels in Pumped Wells

Water levels measured in pumped wells are affected to an uncertain degree by the efficiency of the well, which in turn is often described in terms of linear and/or non-linear well losses (*Groundwater and Wells* [Driscoll 1986]; *Analysis and Evaluation of Pumping Test Data* [Kruseman and de Ridder 1990]; EPA 600/R-08/003). In particular, water levels measured in extraction wells are often significantly lower than the water level in the aquifer immediately outside of the well. As a result, the inclusion of water levels measured in extraction wells in water-level maps (whether prepared using the method described in this document or any other method) is typically inadvisable, since it exaggerates the drawdown within the aquifer due to pumping, which in turn can lead to systematic over-estimation of the extent of capture.

The method described in this document usually obviates the need to directly include water levels measured in extraction and injection wells in the data used to prepare maps. However, circumstances may be encountered where it might be reasonable to include these data in the mapping. This principally occurs where there is a very low density of monitoring wells in the vicinity of the pumped well(s) and one or both of the following apply:

- Where a detailed analysis of well efficiency has been undertaken, ideally across a range of extraction rates, so the water level can be corrected for well losses. However, since well efficiency is a non-linear function of the pumping rate that often declines over time, in most applications, correcting water levels measured in pumped wells for inclusion in the mapping is very difficult.

- Where a piezometer, sometimes referred to as a "dosing point," is installed within the extraction well filter pack, between the well screen and the native aquifer materials. It is noted, however, that water levels measured using piezometers installed within the filter pack can themselves exhibit an uncertain amount of inefficiency that depends on the well drilling and development techniques, as well as the relationship between the filter pack and native aquifer materials.

As a result, in most cases it is more instructive to compare the mapped water level estimated at a very small distance from each pumped well with the level measured within the pumped well or dosing well, rather than explicitly including these measured water levels in the mapping.

4.1.3 Compilation and Management of Data

The data required to implement the methods described are commonly compiled and managed as part of remedy performance monitoring activities. As such, there is no particular additional data compilation or management requirements. However, since the water level and capture mapping comprise a quite sophisticated analysis that the practitioner may wish to reproduce, revisit, or demonstrate to interested parties, it is beneficial to construct and archive a project/analysis-specific database that lists all of the input data, as well as a descriptive summary of the analysis. The data are most readily compiled and archived in Microsoft Excel® or Access® files, particularly since the KT3D_H2O program that implements the mapping and particle-tracking methods readily reads data from these file formats.

4.1.4 Data Processing – Corrections for Barometric Efficiency

Water levels within wells and within aquifers respond to variations in atmospheric pressure. These barometric fluctuations are expressed as an areal, relatively uniform stress applied directly at the land surface and to the open well water-level surface. The manner in which a well/aquifer system responds to changes in atmospheric pressure is variable and related to the degree of aquifer confinement and to the storage and transmission characteristics of the well/aquifer system. However, it is generally the case that water-level elevations measured within monitoring wells are not equivalent to the water table elevation or hydraulic head within the aquifer adjacent to the well ("Identifying and Removing Barometric Pressure Effects in Confined and Unconfined Aquifers" [Rasmussen and Crawford 1997]; PNNL-13078, *Effects of Barometric Fluctuations on Well Water-Level Measurements and Aquifer Test Data*; "Considering Barometric Pressure in Groundwater Flow Investigations" [Spane 2002]). This is due primarily to the transient imbalance between the barometric pressure that is applied instantaneously to the fluid column within an open well and the delayed transmission of the barometric pressure through the vadose zone to the water table surface. While the use of vented data loggers to record water levels in wells accounts for the direct barometric effects on the water level measured within the well, this does not account for the delayed transmission of the barometric pressure changes through the unsaturated zone to the aquifer.

Rasmussen and Crawford (1997), PNNL-13078, and Spane (2002) demonstrate that barometric pressure fluctuations can be removed from measured water levels using a multiple-regression deconvolution technique, which improves the detection and analysis of hydrologic stresses imposed by pumped wells as observed at monitoring wells. Although corrections of this type have not been made for purposes of water-level mapping using the methods described, such corrections may be advisable in some aquifer settings in particular areas of very low hydraulic gradients where barometric effects impact hydraulic gradient calculations and, hence, groundwater flow directions and rates.

4.1.5 Variography

This document does not provide a detailed discussion on methods for estimating the form and parameters of the variogram. General geostatistical texts, including Isaacs and Srivastava (1989), Deutsch and Journel (1998), Chiles and Delfiner (1999), and references therein contain further detailed discussion. Co-variance estimation in the presence of a drift is described in considerable detail by Kitanidis (1993) and Kitanidis (1999). However, the following should be considered when using the mapping method described.

The variogram (or semi-variogram) is a function that describes the spatial dependence correlation within a random field. Intuitively, in the context of two-dimensional water-level mapping, the variogram describes how much information the knowledge of the head $h(x,y)$ provides regarding the expected value

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of the head $h(x_1,y_1)$, with increasing separation distance ($\sqrt{(x-x_1)^2+(y-y_1)^2}$). In stationary ordinary kriging (i.e., kriging without a trend), the form and parameters of the variogram function are typically estimated by calculating an empirical variogram using the measurement data and modeling (analyzing and fitting a function to) this empirical variogram, using one or more common variogram models.

When using universal kriging to interpolate spatial data, the variogram is generally used to describe the spatial dependence or correlation in the residuals from the underlying drift (i.e., in the term $\varepsilon(x,y)$ appearing in Equations 2-5, 2-8, and 2-11). As described by Kitanidis (1993), a deterministic trend (i.e., universal kriging) should only be used when there is a sound basis for doing so. On these occasions, the use of an appropriate trend that explains the majority of the pattern (i.e., spatial dependence or correlation) in the water-level data using functions that have a firm hydrologic foundation leaves considerably less of the "total" (co-)variance to be explained using the variogram, and generally leads to smaller predictive (interpolation) error (Kitanidis 1993). The use of an appropriate deterministic trend can also mitigate difficulties that are often encountered with unrealistic extrapolation beyond the convex hull of the measurement data when using stationary ordinary kriging.

In the context of water-level mapping using the methods described, if the assumptions that underlie the form(s) of the drift(s) used (i.e., Equations 2-5, 2-8, or 2-11) were strictly honored, and water-levels and pumping rates were known without error, then the drift would explain the water levels exactly and there would be no residual from the drift. Clearly, this is unlikely to occur in practice. Under the assumption that a suitable drift has been specified, factors that lead to non-zero residuals include the following (this is not an exhaustive list):

- Errors in the measurement of water levels
- Errors in the pumping rates recorded at wells
- Heterogeneity of aquifer properties
- Non-uniform distribution of recharge (in the case of water table aquifers) or leakage (in the case of leaky aquifers).

If these factors can be considered random (stationary), then the most appropriate approach is typically to (1) fit the drift using ordinary least squares, which is offered by some software programs but otherwise may be accomplished by specifying a horizontal (pure nugget) variogram; (2) calculate the residuals from this drift; and (3) fit a suitable variogram model to the empirical variogram calculated using these residuals (Kitanidis 1993). When mapping a large number of water-level data sets, calculating and evaluating the residuals for each occasion that the drift is fitted can be tedious. The KT3D_H2O program enables residuals to be calculated automatically for one or more data sets. If more than one data set is available, the program enables plotting of all or a subset of the calculated empirical variograms and the selection of an "ensemble" variogram suitable for use with all data sets.

On many occasions, the number of data points available for constructing an empirical variogram and preparing a water-level map is relatively small, leading to significant uncertainty in defining the "best" variogram. In these instances, the best that might be hoped for is to identify the approximate variance of the residuals (variogram sill) and the approximate separation distance at which this variance is attained (i.e., variogram range). If the residuals are relatively small, the choice of variogram structure may have little effect on the interpolated water levels and, hence, the estimated extent of capture. However, if the residuals are large (and the appropriateness of the drift model is assured), a pragmatic approach is to complete the analysis using two or more reasonable variogram structures defined on the basis of the estimated variance and range parameters, and then compare the maps produced.

4.1.6 Mapping Frequency

While maps can be prepared on any frequency for which sufficient data are available, a review of the available water-level data and, perhaps more importantly, review of the pump-and-treat remedy operations data together with an understanding of other transient stresses on the aquifer, is advisable to discern the appropriate mapping frequency. For example, although water-level and pumping data may have been recorded weekly at a site, the pumping data may distinguish changing pumping rates over time, which can be described in terms of two or more distinct periods during which the rates were relatively constant. Karanovic et al. (2009) demonstrate the value of calculating CFMs for distinct periods in the lifecycle of a remedy and contrasting these CFMs to help discern the likely benefits of changes in remedy operations.

Decisions regarding mapping frequency are best reached based on knowledge of the mathematics underlying the mapping approach and knowledge of site characteristics, including remedy operations. This is illustrated below using an idealized hypothetical site and a more complex hypothetical site that is bounded by a river.

4.1.6.1 Ideal Hypothetical Site

At the first site, a single extraction well and injection well pair (such as described by Tonkin and Larson 2002) recover and reinject water from a confined aquifer with lateral boundaries located a great distance from the wells. The wells penetrate the full aquifer thickness. Since the aquifer is confined, transmissivity is constant. The wells pump at constant rates year round, and there are no temporal changes to groundwater flow directions and rates. Finally, groundwater-level measurements are made without error.

At this site, it is appropriate to use Equation 2-5 to map groundwater elevations, with the extraction and injection well included in the same drift term. The following apply when estimating the head in the aquifer using Equation 2-5:

- Background hydraulic gradients are constant. As such, the first three terms of Equation 2-5 that define uniform horizontal flow are constant.
- Groundwater extraction and injection rates are constant. As such, the fourth term of Equation 2-5 that corresponds to pumping is constant.
- Measurement error is zero. As such, the final term of Equation 2-5 is zero.

At this ideal site, mapping using Equation 2-5 on any occasion reproduces the exact, quasi-steady-state water-level surface. As a result, a single depiction of the water-level surface would provide the correct potentiometry and an accurate depiction of capture.

4.1.6.2 More Complex Hypothetical Site

At the second site, several extraction and injection wells recover and reinject water from an unconfined aquifer, producing drawdown and mounding that is a relatively small fraction of the aquifer saturated thickness. The aquifer is mildly heterogeneous and is bounded on one side by a large river that exhibits seasonal changes in groundwater elevation of several meters, resulting in substantial changes in groundwater flow directions and rates hundreds of meters distant from the river. Recharge to the aquifer is negligible. The extraction and injection wells penetrate the majority of the aquifer saturated thickness during low river stage. Extraction and corresponding injection rates change through the year, primarily as a result of changes in saturated thickness due to the changing river stage. Extraction and injection rates are recorded continuously. The extraction and injection wells fall into two groups: the first group is located in an area of relatively high transmissivity, and the second group is located in an area of relatively low transmissivity. Finally, groundwater-level measurements are not made without error, although the errors are random and of relatively small magnitude.

At this site, it is appropriate to use Equation 2-8 to map groundwater elevations, with the two extraction and injection well groups collected into separate drift terms, and a line sink drift term incorporated to approximate the effect of the river on groundwater levels and gradients. The following apply when estimating the head in the aquifer using Equation 2-8:

- Hydraulic gradients change within the mapped area due in part to the river stage, but regionally are relatively constant. As such, the first three terms of Equation 2-8 that define uniform horizontal flow may or may not be considered constant.
- Groundwater extraction and injection rates vary seasonally. As such, the fourth term of Equation 2-8 that corresponds to pumping varies throughout the year.
- The river stage varies seasonally. The change in exchange rate between the aquifer and river is unknown, but water levels in the aquifer clearly reflect the changing river stage.
- Measurement errors are non-zero. As such, the final term of Equation 2-8 is not zero but has a small value.

At this site, mapping using Equation 2-8 on any occasion using coincident groundwater levels, extraction rates, and injection rates does not reproduce the exact water-level surface. Instead, an approximate depiction is obtained of the water levels at that particular time. The conditions represented by this map do not persist for a long time. As a result, a single map of the water-level surface is unlikely to accurately depict the "instantaneous" extent of capture and/or the effects of the changing stresses on this extent. Furthermore, since the principal stresses on the system (i.e., the river stage and pumping rates) do change over time, a single map constructed using average water levels and pumping rates may not accurately depict the "average" or typical extent of capture (e.g., "Sources of Water to Wells for Transient Cyclic Systems" [Reilly and Pollock 1996]; Festger and Walter 2002).

At this site, a single monitoring event is probably insufficient to characterize the time-variant capture zone. Water-level maps prepared at key times (e.g., during high-, low-, and mid-river stage) would help characterize the impact of river stage on gradients and capture. However, since these effects persist for varying amounts of time, and pumping rates also vary, developing a representative (e.g., time-weighted) depiction of capture using this approach is difficult. As a result, preparing water-level maps on a more frequent basis (e.g., monthly or weekly) and constructing a CFM may be the most suitable approach for contrasting (1) areas that are likely within the capture zone at all times under all conditions, (2) areas that are within the capture zone at some times under some conditions and not at others, and (3) areas that are unlikely to be captured under current remedy operations.

4.2 Particle Tracking

After the water-level maps have been prepared, one or more of three common particle-tracking approaches can be used to depict approximate flow directions and rates, and approximate the extent of capture:

1. Forward tracking using particles released throughout the entire mapped area:
    a. This approach is generally used to depict the full extent of capture developed by the extraction wells, given the prepared map(s).

   b. This approach can be somewhat computationally intensive.

2. Reverse tracking, using particles released in one or more circles around each extraction well:

   a. This approach is generally used to identify, given the prepared map(s), the approximate source(s) of water recovered by each extraction well (as indicated earlier, estimates of the extent of individual well capture zones are often not as reliable as estimates of system-wide capture).

   b. This approach is computationally efficient but can be misleading if not combined together with method 1.

3. Forward tracking, using particles released only throughout the extent of contamination that exceeds target cleanup levels:

   a. This approach is generally used to identify whether, given the prepared map(s), the area targeted for remediation will ultimately be contained and recovered.

   b. This approach often offers a compromise between the two methods described above.

4.3 Interpreting Results

This document does not include a rigorous discussion of error analysis, as the primary intent is to describe some advantages of the method over more common methods of water-level mapping in the vicinity of pumped wells. However, some basic considerations are described in the following subsections that can indicate the likely reasonableness of the mapped water levels and estimated extents of capture.

4.3.1 Reasonableness of Mapped Surfaces

The method described often produces a gridded surface that reasonably depicts conditions at the site and is suitable for use with particle tracking to evaluate capture. The reliability of the water-level maps and their use with particle-tracking arises largely because the method reproduces measured water levels and the corresponding hydraulic gradients, and it also produces maps that approximately conserve flow. The reasonableness of the mapped surface can generally be considered in terms of the following:

- Is the drift model suitable, and appropriately defined?
- If the drift model is suitable, what is the magnitude and distribution, and what are the sources, of residual error?

Assessment of the reasonableness of the mapped water-level surfaces typically focuses on evaluating these factors.

4.3.1.1 Qualitative Review

The foremost methods of evaluating the mapped surfaces and contours are qualitative, comprising the following evaluations undertaken in the context of the conceptual site model:

1. Do the contours indicate drawdown (convergent flow) and mounding (divergent flow) in the vicinity of extraction and injection wells, respectively?
2. Are the contours consistent with the expected patterns of gain or loss in the vicinity of other features, such as water bodies?
3. Do the contours suggest groundwater flow in a direction and at a rate consistent with the CSM?

4. Are the effects of lateral boundaries (whether explicitly incorporated in the drift or not) evident?
5. Is there evidence of local anomalies (e.g., concentric "bullseye" patterns around some monitoring wells, or rapidly changing gradients [contour spacing] between monitoring wells)?

With regard to item (1) above, it is important to realize that as currently implemented, the regression that underpins universal kriging does not explicitly ensure that the estimated regression coefficients are positive (or negative) (i.e., the regression coefficients can take on either sign). On some occasions, this can result in contour maps that depict mounding (divergent flow) in the vicinity of extraction wells and/or drawdown (convergent flow) in the vicinity of injection wells. On most occasions, the data (including the location of monitoring wells and the actual measured water levels) indicate that the water levels do not reflect sufficient drawdown and/or mounding to enable the universal kriging to correctly infer the response to pumping, and/or that the area exhibits features such as inhomogeneities that might be accommodated by separating the sinks/sources into more than one drift term.

With regard to items (2) through (5), the mapping may have identified inconsistencies with the data, including pumping rates, water levels, etc., or difficulty with one or more assumptions made in undertaking the kriging (e.g., grouping of like features within drift terms or the variogram selected). In either case, review of the data, conceptual site model, and the definition of drift terms is recommended.

4.3.1.2 Residual Analysis

Under the assumption that the drift model is suitable and has been defined appropriately, the magnitude and distribution of residuals from the drift help identify the location and degree of deviation from conserved flow conditions. The residual provides an indication of the leverage (as opposed to the influence) that the data location has on the resulting water-level map and, by inference, the capture map. Sources of residual error fall into two broad categories: model error, and measurement error. The spatial distribution of residuals is best appreciated by fitting the drift using ordinary least squares, calculating the residuals from this drift, contouring the drift itself, and contouring and posting (plotting spatially) the residuals. Locations that exhibit a high (positive or negative) residual indicate that a water-level map prepared using the drift, as defined, will likely exhibit a significant departure from the drift, and as a result may depart significantly from the conservation of flow. Whether this is of concern depends on the location and magnitude of the residual, and it is site-specific.

When mapping a large number of water-level data sets, it may be desirable to calculate and evaluate the residuals for each occasion that the drift is fitted. The KT3D_H2O program enables residuals to be calculated and evaluated for one or more data sets.

4.3.1.3 Single-Point (Leave-One-Out) Cross-Validation and Jackknife Analyses

The suitability of the drift model can be assessed qualitatively and/or quantitatively. Qualitative evaluations focus on visually comparing maps prepared using different assumptions for the drift model (e.g., excluding components of the drift; visually comparing maps of the distribution and magnitude of residuals from the underlying drift when alternate assumptions are used). Single-point cross-validation and/or "jackknifing" (Deutsch and Journel 1998) may be used in a manner that can be considered quantitative analogues of these qualitative assessments. These methods are a measure of the statistical influence that the omission (or addition) of measured data has on the estimated (fitted) values of the drift coefficients (*The Jackknife, the Bootstrap, and Other Re-Sampling Plans* [Efron 1982]; *Nonlinear Regression* [Seber and Wild 1989]; Deutsch and Journel 1998). Some suggestions for the use of quantitative influence methods in the context of water-level mapping are provided below; however, the interpretation of such analyses is not straightforward since the prediction if interest is *not* the statistics of the map itself, but the more nuanced inference for groundwater flow and hydraulic capture. Ideally, when conducting single-point cross-validation or jackknifing, the analysis would produce a CFM for each suppressed point/subset of points, and inference would be based on the differences between these maps; however, this may often be computationally intensive. The program KT3D_H2O enables single-point cross-validation with reporting of simple estimation error statistics, but it does not enable automated jackknifing.

When undertaking single-point cross-validation, the assumed drift is sequentially fit to a subset of *n-1* of the *n* measurement data points, by removing each measurement point in turn. Results are often evaluated in terms of the sum-of-squared difference between the measured value and its equivalent, as calculated using the drift, although other statistics are also used (e.g., Efron 1982). Those locations that exhibit a large sum-of-squared difference possess a large influence on the estimated coefficients of the underlying drift. By inference, it is likely that water-level maps prepared including and excluding points possessing high-influence statistics may be quite different, and the mapped capture may also differ significantly. Quantitative interpretation of these influence statistics can be difficult in the context of water-level mapping. It can be evaluated by actually preparing the maps that result from suppressing each point in turn; however, this can be computationally demanding. It is generally the case that locations exhibiting high influence for the hydrologic drift term coefficients lie close to internal sinks/sources and/or boundaries, and (indicating that independent information regarding these sinks/sources and/or boundaries should be evaluated) locations that exhibit high influence for the linear (planar) drift coefficients that define the background gradient often lie some distance from the centroid of the measurement locations.

When using jackknifing, the assumed drift is sequentially fit to a subset of *n-k* of the *n* measurement data points by removing *k* measurement points in turn. In this case, the results are often evaluated in terms of differences in the estimated drift coefficients, although other statistics are also used. Again, quantitative interpretation of these influence statistics can be difficult in the context of water-level mapping. It is usually most instructive to prepare water-level (and capture) maps including and excluding the *k* points if this is computationally feasible.

4.3.2 Rule-of-Thumb Calculations of Capture Extent

The following relationships can sometimes be used to help determine if the extents of capture calculated using the mapping technique are likely to be reasonable.

Noting that all variables must have consistent units, the idealized capture zone for a single fully penetrating well extracting groundwater at a constant rate within a fully confined aquifer of infinite lateral extent exhibiting steady, unidirectional groundwater flow can be described using the following relationships:

- The ultimate width of the capture zone, W_{ult}, far upgradient from the pumping well is equivalent to the pumping rate divided by the hydraulic gradient multiplied by the aquifer transmissivity (Equation 4-1):

$$W_{ult} = \frac{Q}{Ti}$$ **(Equation 4-1)**

- The width of the capture zone at the pumping well, measured along the line perpendicular to groundwater flow, is one-half of the ultimate width (Equation 4-2):

$$W_{well} = \frac{Q}{2Ti}$$ **(Equation 4-2)**

- The distance from the extraction well to the stagnation point (in two dimensions, the point downgradient of the extraction well at which the hydraulic gradient is zero and which represents the limit of the downgradient extent of capture) is equivalent to the ultimate width divided by 2π (Equation 4-3):

$$d_{sp} = \frac{Q}{2\pi Ti}$$

(Equation 4-3)

These formulas change in an unconfined aquifer. With no recharge, a horizontal base and small drawdown relative to the initial saturated thickness of the aquifer, and assuming that pre-pumping heads are available at two points (h_1 and h_2) separated by a distance L that is measured along the regional gradient, the following relationships apply:

- The ultimate width becomes as shown in Equation 4-4:

$$W_{ult} = \frac{2QL}{K(h_2^2 - h_1^2)}$$

(Equation 4-4)

- The width at the well becomes as shown in Equation 4-5:

$$W_{well} = \frac{QL}{K(h_2^2 - h_1^2)}$$

(Equation 4-5)

- The downgradient distance to the stagnation point becomes as shown in Equation 4-6:

$$d_{sp} = \frac{QL}{\pi K(h_2^2 - h_1^2)}$$

(Equation 4-6)

4.3.3 Multiple Lines of Evidence

Basic considerations such as those described above can indicate the likely reasonableness of the mapped water levels and resulting estimate(s) of capture. As recommended in EPA 600/R-08/003, it is advisable that multiple lines of evidence (which consider a wide range of data types including water levels, pumping rates, changes in concentrations, etc.) be used to infer the performance of a pump-and-treat remedy.

5 Recommendations for Monitoring Program Design

This chapter provides general recommendations for obtaining water levels and additional data that may enable the methods described to be used with confidence. These recommendations are based primarily on previous applications of the method and are not prescriptive. This chapter does not provide a comprehensive discussion that can be used to design monitoring programs; instead, it highlights elements that should be considered when designing a monitoring program for purposes of evaluating hydraulic capture. Since the conditions encountered at each site differ, it is likely that not all factors described will be required or considered at every site.

5.1 Spatial Distribution of Water-Level Monitoring

Since the drift described by Equations 2-5, 2-8, and 2-11 is assumed to apply to the entire data set (i.e., local data neighborhoods are rarely used) the regression coefficients of Equations 2-5, 2-8, and 2-11 are calculated from a global estimation of $h(x,y)$. Under most conditions, all measured water-level data affect the estimated coefficients of the drift and, hence, the water-level and capture maps. As described earlier, however, some locations may exhibit a larger leverage or influence on the drift and resulting maps than other locations. In consideration of common recommendations for data density and distribution for estimating the variogram, the ideal monitoring program might comprise a uniform distribution of monitoring locations, supplemented by additional monitoring in the vicinity of internal sinks/sources. Such a monitoring program would provide information for identifying the drift coefficients, and also for analyzing and evaluating residuals from the fitted drift. However, such monitoring density is rarely encountered, and while statistical methods might be used to identify key locations and develop suitable monitoring programs, qualitative recommendations can be developed by considering (1) the form of Equations 2-5, 2-8, and 2-11; (2) the patterns of mounding and drawdown that arise from the internal sinks/sources described by these equations; and (3) the effect of lateral boundaries. This is illustrated using three hypothetical sites that include one or more point sinks/sources. Similar qualitative recommendations can be made for sites possessing features represented by the line sink/source and circular source drift terms.

At the first site, a single, fully penetrating extraction well pumps from a homogeneous confined aquifer of infinite aerial extent that exhibits uniform flow prior to pumping, and at which water-level measurements are accompanied by small-valued random error. Equation 2-4 states that pumping at the well causes a pattern of drawdown that is concentric about the well and that diminishes linearly with the logarithm of the distance from the well. This relationship is often used to design and analyze tests to estimate aquifer properties by spacing monitoring wells at increasing distances from the pumped well and completing distance-drawdown analyses. Collectively, this suggests that obtaining water levels at a site from a monitoring location close to the pumped well, plus additional locations at increasing distances from the pumped well, will provide water-level data that reflect (1) the drawdown due to pumping since this "signal" will exceed the "noise" arising from measurement error; and (2) the background gradient, without requiring a large number of additional monitoring locations.

At the second site, several fully penetrating wells pump from a similarly ideal aquifer. Consistent with the discussion above, the ideal monitoring program would comprise a monitoring location close to each pumped well and additional monitoring at increasing distances from each well. Using this approach, as the number of pumped wells increases, the number of monitoring locations also increases, which can become costly. However, if the aquifer is homogenous or only mildly heterogeneous as described, each pumped well is of similar construction, and pumping is recorded continuously at each pumped well, then it may be reasonable to reduce the number of monitoring locations. This is possible because (1) the response of the aquifer to each pumped well will be similar so monitoring at a smaller number of wells should condition the kriging by providing drift coefficients that apply for all wells, and (2) the pumping data can be reviewed to ensure that each well was pumping on each occasion a map is prepared. This is necessary since this information cannot be reasonably inferred for pumped wells that do not have a nearby water-level monitoring location.

At the third site, several pumping wells penetrate most, but not all, of the saturated thickness of a quite heterogeneous unconfined aquifer. In this case, the response of the aquifer to pumping at each well can be expected to differ substantially. As a result, it may be necessary to monitoring water levels at a location close to each pumped well to ensure that the unique response in the vicinity of each well is captured in the water-level maps.

In summary, while the mapping technique produces reasonable water-level depictions in the vicinity of pumped wells without requiring a very high density of monitoring, it is nonetheless generally the case that monitoring networks comprising a relatively large number of locations will produce more reliable maps than those comprising a relatively small number of locations. Furthermore, the omission of measured water levels in the vicinity of pumped wells, combined with the presence of substantial error accompanying water-level measurements, may lead to a "muted" surface similar to that obtained without the point sink/source drift term, in turn leading to an erroneous estimate of capture.

5.2 Monitoring of Other Features

5.2.1 Pumped Wells

As stated in Section 4.1.1, it is important that approximate pumping rates are known for each occasion that the water levels will be mapped, and it is critical that the remedy is operating when water levels are recorded/measured. As previously described, as long as pumping rates are known within a constant multiplier, the map that results from the application of Equations 2-5, 2-8, and/or 2-11 will be unaffected by the use of relative rather than absolute rates (although it is good practice to use consistent dimensions and units, and as accurate data as possible). If maps are prepared for a time when relative rates are unknown (or worse, at a time that the system was not operating), the resulting maps may be nonsensical.

For this reason, and other reasons related to both recording and mapping frequency, it is preferable that pumping data are obtained for each individual well so well-specific rates can be confidently assigned, and for the entire system (e.g., combined influent and/or effluent totalizer[s]) so a volumetric balance between the sum of the individual well rates and the combined system rate can be calculated. As a result, the automated data recording that is provided by electronic flow meters tied into a treatment system data recording device (e.g., a programmable logic controller/supervisory control) and data acquisition or similar system is greatly preferred over intermittent manual measurements obtained using flow meters or other methods.

5.2.2 Other Internal Sinks/Sources

The drift terms described by Equations 2-6 and 2-7 and Equations 2-9 and 2-10 describe internal sinks/sources to groundwater that typically represent surface water features such as rivers, ponds, impoundments, and trenches. In these cases, the rate of exchange of water with the groundwater system is usually unknown. However, the elevation of the water in such a body may be measured manually using a gauge that is tied to the appropriate site vertical reference datum, or automatically using a pressure transducer and data logger. This elevation can be incorporated into the mapping to condition the fit of the drift coefficient corresponding to each feature.

In the case that the mapped area contains a single such feature that is represented by a single corresponding drift term (and it is only necessary to approximate the impact of the feature on relatively distal water levels), it may not be necessary to obtain frequent elevation measurements corresponding to this feature. However, if the mapped area contains several such features represented by several drift terms, and/or if it is necessary to approximate the extent of the groundwater that exchanges with (leaves or enters through) one or more of these features, then more frequent elevation measurements will be required. In the latter case, the use of pressure transducers and data loggers may be appropriate.

5.3 Monitoring Frequency

The frequency of monitoring in regard to automated continuous data is discussed in this section. Hypothetical examples for monitoring frequency are also provided.

5.3.1 Automated Continuous Data

At many sites, water levels and other data can be obtained using electronic equipment that records and stores data for later retrieval and analysis. For a variety of reasons, collecting continuous data can lend enormous credibility to a mapping analysis.

Continuous water-level data, such as obtained using a pressure transducer and data logger, are beneficial for the following reasons:

- The data are relatively easy to collect once the necessary instrumentation has been installed.
- The data are relatively cheap to obtain once the initial capital investment has been made.
- The data integrate the effects of multiple stresses, such as changing pumping rates, over time and as a result these can be used:
  - Directly in mapping analyses and the preparation of CFMs to infer remedy performance
  - Indirectly, through calibration, with numerical models that may be used for a variety of purposes.

At many sites, it may not be feasible or necessary to record water levels at every monitoring well using pressure transducers and data loggers. Generally, a subset of wells will be instrumented in this manner, and water levels will be obtained manually from the remaining wells on a less frequent (e.g., quarterly) basis using an electronic tape. At such sites, it is advisable that those wells located in areas likely to exhibit widely ranging water levels (e.g., in response to pumping or other stresses) be instrumented to obtain frequent water-level data, with water levels from wells located in areas likely to exhibit very little change over time obtained manually.

Continuous pumping data, such as obtained using electronic flow totalizers and supervisory control and data acquisition or similar systems, are beneficial for the following reasons:

- The data are relatively easy to collect once the necessary instrumentation has been installed.
- The data enable the identification of system "on" and "off" periods, to ensure that a capture analysis is not undertaken for a period when extraction and/or injection were not taking place.
- The data enable identification of periods during which relatively constant pumping rates were maintained.
- The data may enable a time-weighted evaluation of capture over a defined period, by considering the extent of capture during periods of pumping and the absence of capture during periods of non-pumping.

Groundwater extraction and injection can be conducted either at a constant rate (in which case the pumping rate does not vary over time) or using a level- or float-control that triggers pumping under certain conditions. In the case of constant-rate pumping, there can be a reasonably high degree of confidence that the pumped wells are operating at relatively consistent rates prior to and during the time that the water levels are measured. In the case of intermittent pumping that is triggered by a level setting in the pumped well, there is considerably less certainty as to whether (and at what rates) the pumped wells are operating at the time that water levels are measured. In this case, the use of automated flow totalizers and/or devices that record the number of times that pumping was triggered in each well is recommended.

Finally, while the use of automatic data-collection equipment is highly recommended, it is vital that data obtained using automated techniques be verified using independent means. In the case of water levels, records obtained within each well instrumented with a pressure transducer should be corroborated and/or corrected using data obtained manually using an electronic tape or similar device. In the case of pumping data, analyses of flow rates should be used to corroborate the rates that are used in the mapping.

5.3.2 Hypothetical Examples

The appropriate frequency for monitoring water levels and other features such as pumping rates at wells is site-specific. However, some suggestions can be developed based on knowledge of the mathematics that underlie the mapping approach and knowledge of the site characteristics. This is illustrated using the ideal hypothetical site and more complex hypothetical site, as described in Section 4.1.

At the ideal site, the background hydraulic gradients are constant. As such, the first three terms of Equation 2-5 that define uniform horizontal flow are constant; the groundwater extraction and injection rates are constant, so the fourth term of Equation 2-5 that corresponds to pumping is constant; and measurement error is zero, so the final term of Equation 2-5 is zero. At this ideal site, mapping using Equation 2-5 on any occasion reproduces the exact water-level surface. As a result, a single depiction of the water-level surface provides the correct potentiometry and an accurate depiction of capture. At this ideal site, a single monitoring event is sufficient to characterize the time-invariant capture zone. As a result, it would likely not be cost effective to invest in automated water-level monitoring.

At the more complex site, the background hydraulic gradients may or may not be constant, the groundwater extraction and injection rates vary throughout the year, the river stage varies seasonally, and measurement error is not zero. At this site, because the principal stresses on the system (i.e., the river stage and pumping rates) change over time mapping of water levels obtained from a single monitoring event is insufficient to characterize the time-variant capture zone. As suggested in Section 4.1, preparing water-level maps on a more frequent basis (e.g., monthly or weekly) and constructing a CFM may be a suitable approach for contrasting areas that are likely within the capture zone at all times under all conditions with areas that are within the capture zone at some times under some conditions, and not at others. If maps are prepared on a monthly basis, water levels might be obtained manually, whereas if maps are prepared on a weekly basis (or more frequently), then it is likely to be cost effective to obtain water levels using pressure transducers and data loggers. If pressure transducers and data loggers are used, essentially continuous (e.g., hourly) data can be obtained and reviewed to identify a suitable site-specific mapping frequency.

If water-level data are obtained using pressure transducers and data loggers, information on the principal stresses (e.g., the rates at pumped wells and the stage of the river) would ideally be obtained on the same recording interval.

6 Field Examples

This chapter provides example applications of the methods described. The examples are drawn from analyses conducted as part of annual groundwater pump-and-treat remedy evaluations conducted in calendar year 2008 (CY08) at the U.S. Department of Energy Hanford Site near Richland, Washington. Two examples are provided: the first comprises a capture evaluation for the remedy operating at the 100-KR-4 Groundwater Operable Unit (OU), while the second comprises a capture evaluation for the remedy operating in the 200-ZP-1 Groundwater OU. Complete details of the analyses conducted at each OU are provided in the *Calendar Year 2008 Annual Summary Report for the 100-HR-3, 100-KR-4, and 100-NR-2 Operable Unit Pump-and-Treat Operation* (DOE/RL-2009-15), and *200-UP-1 and 200-ZP-1 Operable Units Pump-and-Treat System Annual Report for Fiscal Year 2008* (DOE/RL-2008-77).

The examples illustrate several aspects of the method implementations. The examples do not represent ideal cases, nor is it suggested that the mapping should be relied upon as the sole line of evidence for remedy performance.

The examples are accompanied by discussion of the degree of adherence to the principal assumptions, as well as method(s) used to accommodate or evaluate the impact of violations of these assumptions on the inference of remedy performance.

6.1 100-KR-4 Operable Unit Pump-and-Treat Remedy

6.1.1 Background

The 100-KR-4 OU and adjacent OUs are located along the Columbia River Corridor at the site of the former K Reactor. Groundwater in the vicinity of the 100-KR-4 OU is known to be contaminated with hexavalent chromium and tritium. A pump-and-treat remedy has operated for several years to recover contaminated groundwater and prevent contamination from discharging to the Columbia River. Groundwater levels in the 100-KR-4 OU respond to changes in the Columbia River stage, which in turn impacts the operational extraction rates. Groundwater flow occurs in an unconfined aquifer, which is comprised of moderately permeable sands and gravels of the Ringold Unit E. Flow is generally toward the Columbia River, except during high river stage (which is typically encountered during spring run-off), when flow is locally inland from the Columbia River. The aquifer saturated thickness ranges from about 5 to over 32 m (16 to 105 ft) and is sufficiently transmissive to support current extraction/injection rates of over 1,136 L/min (300 gallons per minute [gpm]). The majority of extraction and injection wells penetrate a substantial portion (typically the majority) of the saturated thickness of the aquifer.

During CY08, groundwater at the 100-KR-4 OU and neighboring K-West was typically extracted from 13 recovery wells, and the treated water injected via 7 injection wells (Figure 6-1). Groundwater levels were measured throughout the 100-K Area continuously at some wells using pressure transducers with data loggers, and intermittently at other wells using manual depth-to-water measurements. A stream gauge is located close to the shoreline. During CY08, two methods were used to estimate the extent of capture:

- Water-level mapping using the method described in this document: The process was repeated for multiple monitoring events throughout CY08 and combined into a CFM.

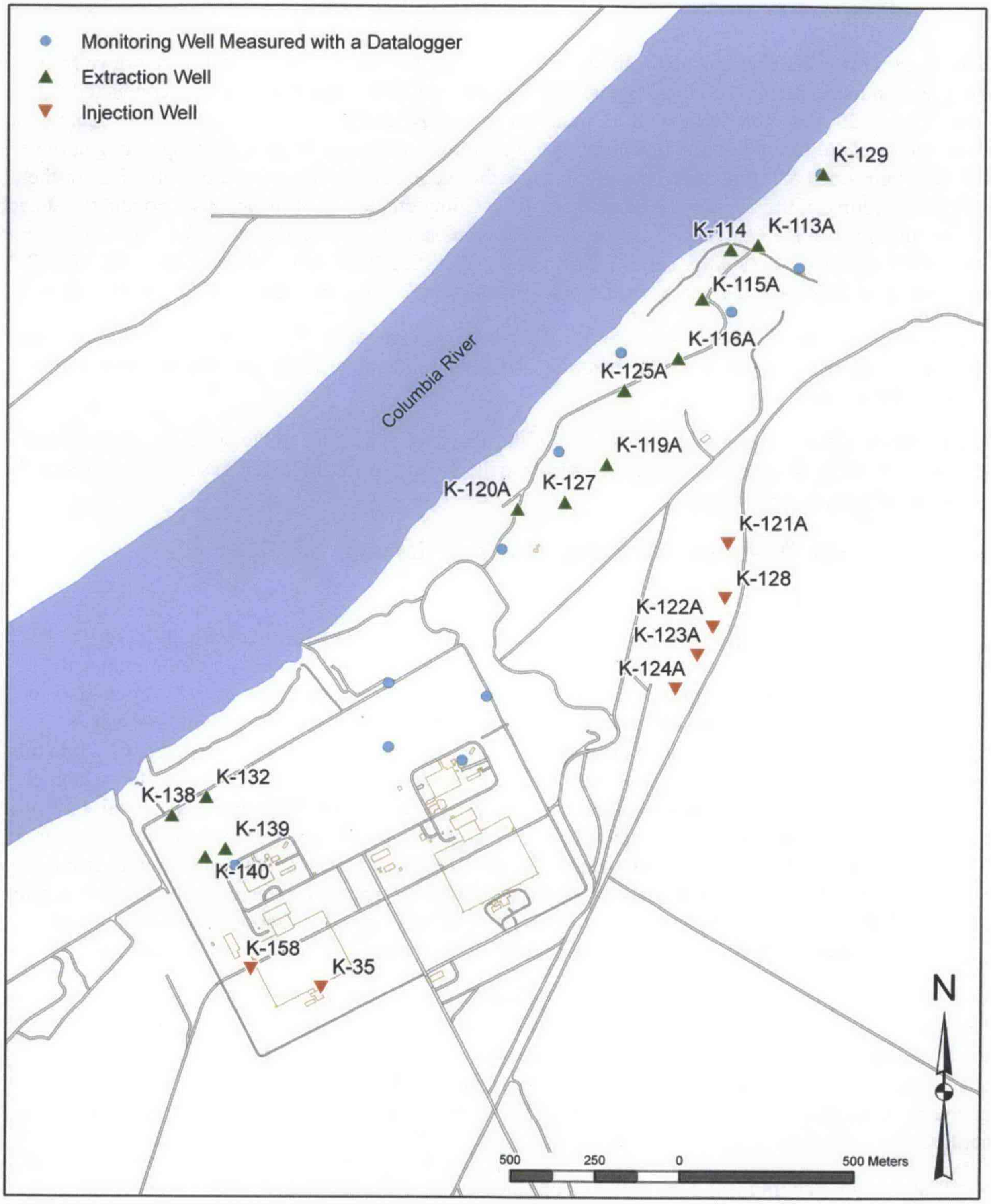


Figure 6-1. 100-K Area Groundwater Pump-and-Treat Systems

- Groundwater modeling using a flow model that encompasses the 100-D, 100-H, 100-K, and 100-N Areas: The model was used to simulate monthly stress periods and depict the approximate the extent of capture using a capture efficiency map (Festger and Walter 2002).

Inference focused on the relative extents and distribution of low and high capture frequencies calculated using the mapping method, and on capture efficiencies calculated using the model. The principal causes for capture frequencies and/or efficiencies that lie between 0 (likely not captured) and 1 (likely captured) are expected to be changing pumping rates and the effects of the changing river stage.

6.1.2 Example

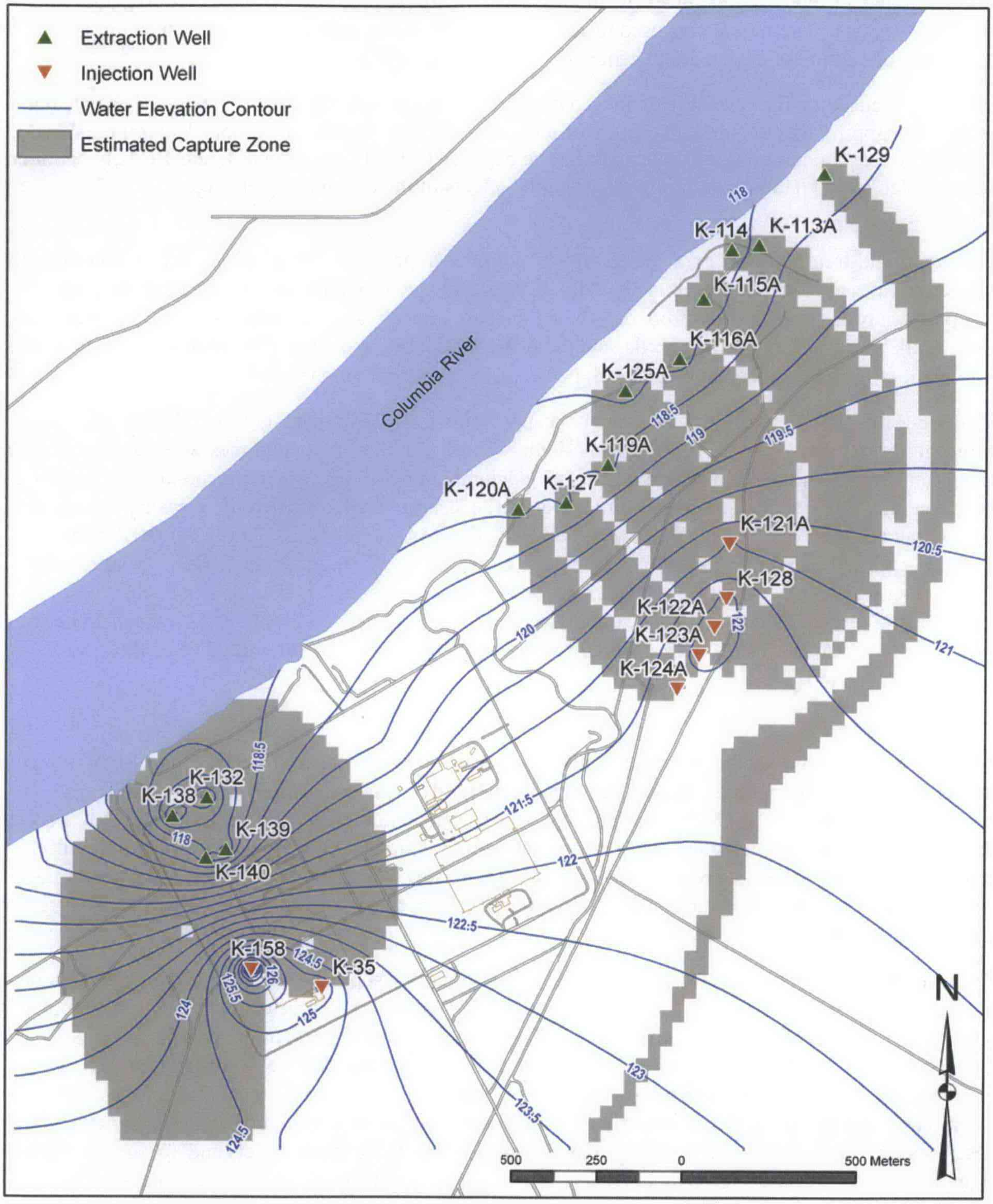
The pump-and-treat system operated intermittently from March to December 2008. When operational, extraction rates averaged approximately 1,401 L/min (370 gpm). Monitoring events identified for the mapping analysis were selected from days when the pump-and-treat system was in operation, water levels were available for all monitoring wells, and the difference between overall extraction and injection rates was small (a high net discrepancy would suggest questionable operational data).

Figure 6-2 illustrates groundwater elevations mapped during fall low-river stage and depicts the approximate extent of capture based on this single water-level event that combines water levels obtained using transducers and manual measurements, the Columbia River stage, and corresponding extraction and injection rates. The shaded area in Figure 6-2 depicting capture was identified by releasing particles throughout the mapped area and recording their fate. Figure 6-3 depicts the CFM calculated using the mapping approach on the basis of 76 groundwater elevation maps generated using daily average water levels, river stage, and extraction and injection rates. Figure 6-3 suggests that gaps in capture (depicted in terms of low capture frequency) may exist between wells 199-K-113A and 199-K-129, and also between wells 199-K-119A and 199-K-127. Similar results were obtained using the groundwater flow model (DOE/RL-2009-15).

6.1.3 Discussion

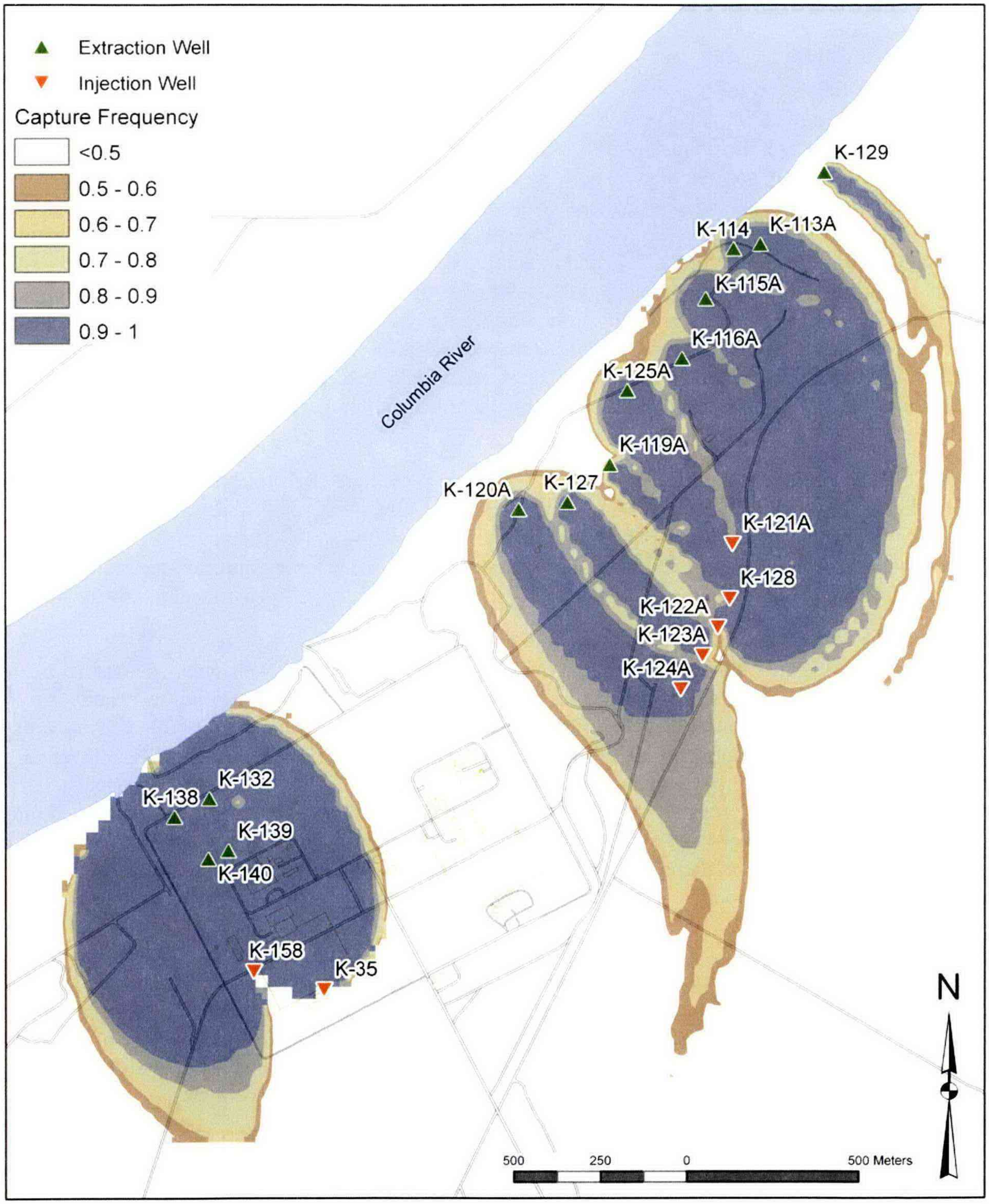
The conceptual model for the 100 Areas suggests reasonable adherence to the following assumptions that underlie the mapping method: negligible vertical flow, fully penetrating wells, and moderate inhomogeneity. However, (1) the aquifer at the 100-K Area is not infinite since it is bounded by a river that exhibits a time-varying stage and recharge/discharge relationship with the aquifer; (2) the aquifer cannot be considered to have reached a quasi-steady state since the changing river stage and pumping rates prevent this; and, (3) in some places, drawdown may reach a substantial (e.g., 20 percent or greater) fraction of the aquifer saturated thickness.

The time-varying stage of the Columbia River is represented by supplementing the groundwater water-level data with measurements of the river stage and using a line sink/source drift that can reflect either a losing or gaining relationship with the aquifer. As a result, some aspects of the non-quasi-steady condition of the aquifer are represented by incorporating the line sink/source and using daily average pumping rates in place of longer-term average rates. The effects of changes in storage and changing saturated thickness due to drawdown at the pumped wells are not explicitly represented. Appendix B describes empirical analyses that suggest that the impact of both transient effects and non-negligible changes in saturated thickness may not deleteriously impact the mapping under conditions similar to those encountered at the 100-K Area.



NOTE: Well numbers are preceded by "199-."

Figure 6-2. Example of Mapped Water Levels and Capture Extents for 100-K Area Groundwater Pump-and-Treat Systems



NOTE: Well numbers are preceded by "199-."

Figure 6-3. Capture Frequency Map for the 100-K Area Groundwater Pump-and-Treat Systems

6.2 200-ZP-1 Operable Unit Pump-and-Treat Remedy

6.2.1 Background

The 200-ZP-1 OU is located within the 200 West Area of the Central Plateau at the site of former Hanford processing facilities. Groundwater in the 200 West Area is contaminated with several constituents of concern, including carbon tetrachloride, chloroform, and technetium-99. An interim pump-and-treat remedy has operated for several years to recover contaminated groundwater. Groundwater levels at the 200-ZP-1 OU exhibit negligible seasonal variation or response to changes in the Columbia River stage and in recent years have been dominated by recession from past wastewater disposal activities, as well as drawdown and mounding due to remediation activities. Groundwater flow occurs primarily within an unconfined aquifer, comprised of moderately permeable sands and gravels of the Ringold Unit E, and flow is generally from west to east, except in the vicinity of extraction and injection wells. The aquifer saturated thickness reaches about 75 m (250 ft) and is sufficiently transmissive to support current extraction/ injection rates well in excess of 1,136 L/min (300 gpm). The hydraulic conductivity varies with elevation within the thick aquifer due to a layered stratigraphic sequence.

During CY08, groundwater at the 200-ZP-1 OU was typically extracted from up to 14 recovery wells, and the treated water was injected via 3 to 5 injection wells (Figure 6-4). Groundwater was also extracted from recovery wells at the 200-UP-1 OU (located south of the 200-ZP-1 OU) and the 241-T Tank Farm (located north of the 200-ZP-1 OU). With one exception, the screened intervals of extraction and injection wells are focused on the upper portion of the aquifer, so all wells penetrate a relatively small fraction of the aquifer saturated thickness.

Groundwater levels are measured throughout the 200-ZP-1 OU continuously at some wells using pressure transducers with data loggers and on a regular basis at other wells using manual depth-to-water measurements. Since a Central Plateau groundwater flow model was under development, the mapping technique provided the primary means of inferring the extent of hydraulic capture during CY08, and inference focused on the relative extents and distribution of the low and high capture frequencies. Water-level mapping was repeated for multiple monitoring events throughout CY08 and combined into a CFM. The principal causes for capture frequencies that lie between 0 (likely not captured) and 1 (likely captured) are expected to be changing pumping rates and other transient effects, in addition to violations in the underlying assumptions.

6.2.2 Example

During CY08, the extraction and injection rates at the 200-ZP-1 pump-and-treat system changed as a result of activities performed to increase the total extraction rate, as well as other activities at the nearby 200-UP-1 OU and 241-T Tank Farm areas. Noting that from August through October none of the systems were operating, the operational data indicate four periods of operation for the collective remedies (DOE/RL-2008-77):

- <u>Period 1, January through May</u>:
  - 200-ZP-1 OU, approximately 833 L/min (220 gpm)
  - 200-UP-1 OU, approximately 34 L/min (9 gpm)
  - 241-T Tank Farm, approximately 189 L/min (50 gpm)

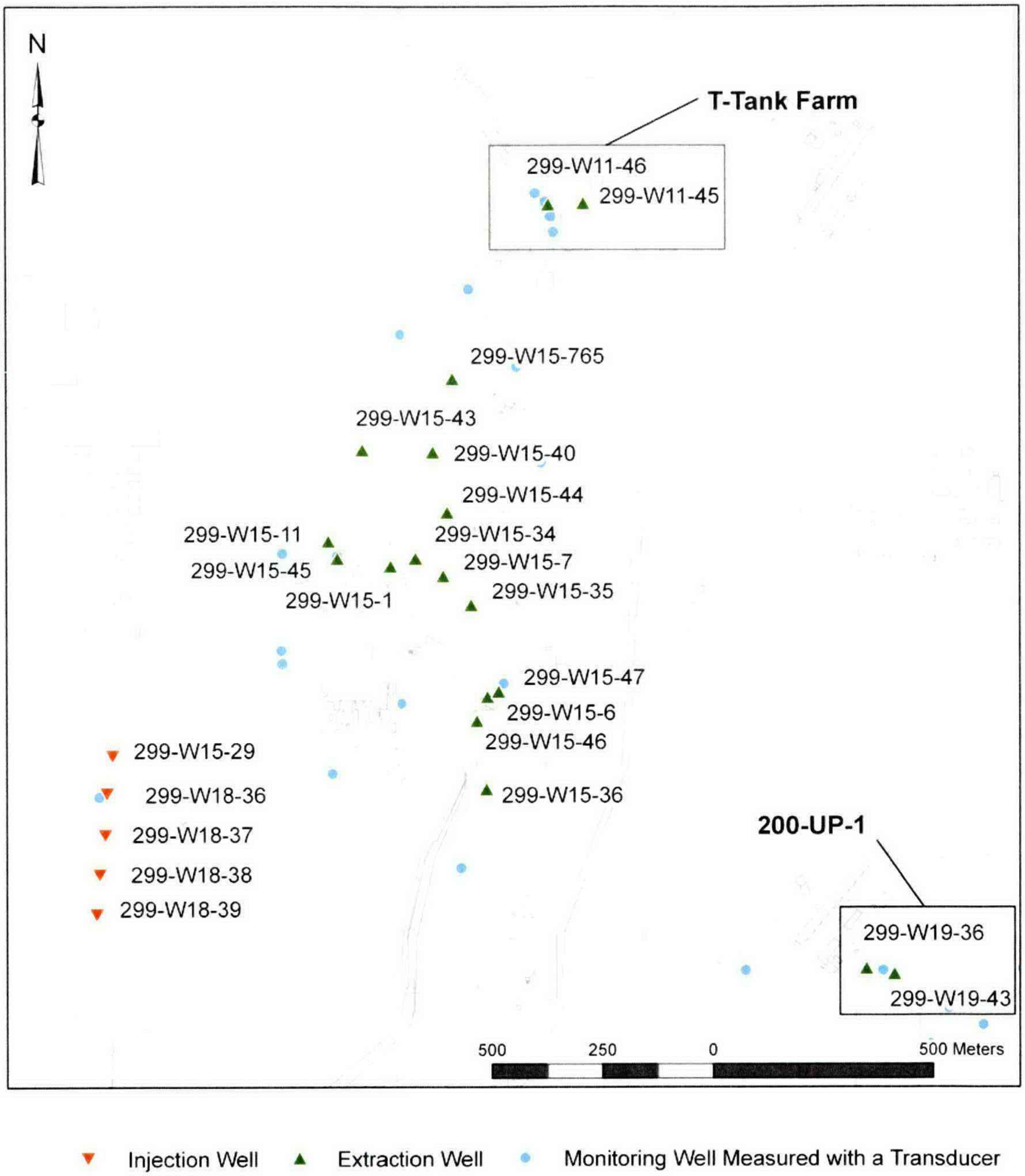


Figure 6-4. 200-ZP-1 and Neighboring 200-UP-1 and 241-T Tank Farm Groundwater Pump-and-Treat Systems

- Period 2, June through August:
  - 200-ZP-1 OU not operational
  - 200-UP-1 OU, approximately 38 L/min (10 gpm)
  - 241-T Tank Farm, approximately 178 L/min (47 gpm)
- Period 3, early November:
  - 200-ZP-1 OU, approximately 1,098 L/min (290 gpm)
  - 200-UP-1 OU and 241-T Tank Farm not operational
- Period 4, mid-November through December:
  - 200-ZP-1 OU, approximately 1,211 L/min (320 gpm)
  - 200-UP-1 OU, approximately 34 L/min (9 gpm)
  - 241-T Tank Farm, approximately 34 L/min (9 gpm).

A comparison of groundwater elevations and the extraction and injection rates indicated that water levels clearly reflect the changing extraction and injection rates at the 200-ZP-1 OU at the end of Period 1 and the commencement of Period 4. As a result, analyses focused on comparing the likely extents of capture during Periods 1 and 4, prior to and following the remedy enhancements that led to an increased extraction rate of about 40 percent. Monitoring events identified for mapping were selected from days when the pump-and-treat system was in operation; water levels were available for all monitoring wells; and the difference between overall extraction and injection rates was small, as a high net discrepancy would suggest questionable operational data.

Figure 6-5 illustrates groundwater elevations mapped during Period 1, prior to the remedy enhancements (shown as map "a" in the figure), and Period 4, following the remedy enhancements (shown as map "b" in the figure). The figure depicts the approximate extent of capture based on each event combining water levels obtained using transducers and manual measurements, as well as corresponding extraction and injection rates. The shaded areas in the figure depicting capture were identified by releasing particles throughout the mapped area and recording their fate. Figure 6-5 suggests that on both occasions, the area-wide gradient was generally from west to east; during both periods, flow converges toward the extraction wells; and the extent of convergent flow toward the extraction wells during Period 4 was greater than during Period 1.

Figure 6-6 depicts the CFM calculated during Period 1, prior to the remedy enhancements (shown as map "a" in the figure), and Period 4, following the remedy enhancements that increased extraction and injection by about 40 percent (shown as map "b" in the figure), using the mapping approach with weekly average water levels and extraction and injection rates. Comparison of the CFMs presented in Figure 6-6 suggests that the mapped water-level data reflect an increase in the extent of hydraulic capture between Periods 1 and 4 that is consistent with the increased pumping rates.

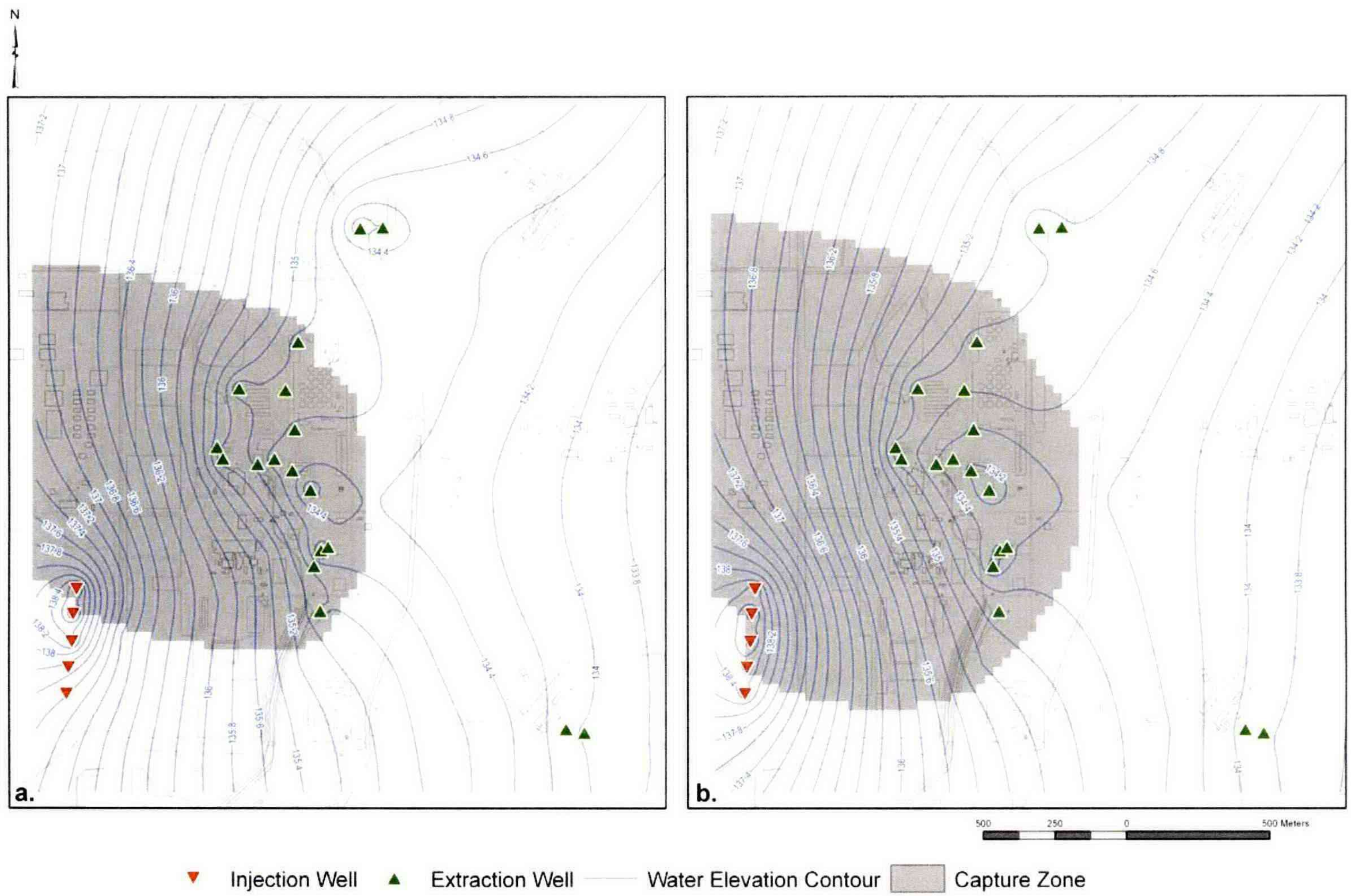


Figure 6-5. Example of Mapped Water Levels and Capture Extents for 200-ZP-1 Groundwater Pump-and-Treat System During (a) Period 1 and (b) Period 4

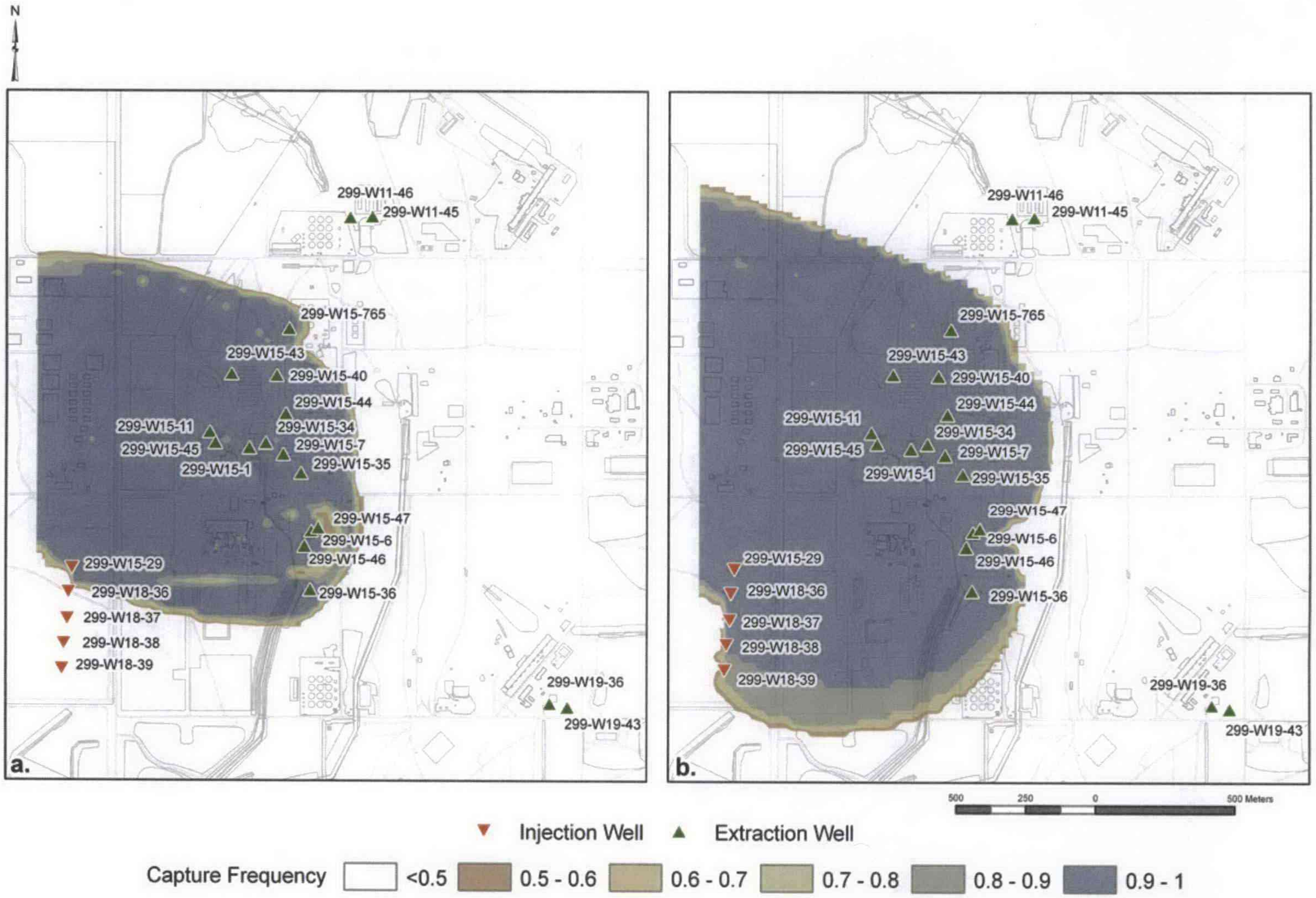


Figure 6-6. Capture Frequency Map for 200-ZP-1 Groundwater Pump-and-Treat System During (a) Period 1 and (b) Period 4

6.2.3 Discussion

The conceptual model for the 200-ZP-1 OU example suggests reasonable adherence to the following assumptions that underlie the mapping method: semi-infinite aquifer (lateral boundaries are relatively distant), quasi-steady conditions due to the absence of a rapidly varying boundary and relatively constant pumping rates within Periods 1 and 4, drawdown that is a relatively small fraction of the saturated thickness, and (perhaps) moderate lateral inhomogeneity within aquifer units. However, (1) the extraction and injection wells at the 200-ZP-1 OU penetrate a relatively small fraction of the aquifer saturated thickness (i.e., partially penetrating), and (2) vertical flows within the aquifer may not be negligible.

The effect of partial penetration was evaluated in the annual report (DOE/RL-2008-77) by calculating partial penetration factors in accordance with the method described by Bair and Lahm (1996), who developed nomographs illustrating the effect of partial penetration on the lateral and vertical extents of capture. This evaluation suggested that, in general terms, the capture estimates obtained from the mapping should not be extended far beneath the screened intervals of the recovery wells, which is consistent with intuition and is a conservative assumption under any circumstances.

The potential impact of vertical flows within the aquifer was not explicitly considered. However, under circumstances such as those encountered at the 200-ZP-1 OU, it might be presumed that substantial extraction within the upper unconfined aquifer, combined with low aerial recharge, would lead to upward flow from intervals beneath the recovery well screens, which suggests that capture extends beneath the wells rather than downward flows from the pumped aquifer sequence (which might suggest the vertical escape of contaminants from the upper intervals of the aquifer that are subject to pumping).

6.3 Summary

At the 100-KR-4 OU, the inference drawn from the mapping corresponded well with the inference drawn from analyses performed using a groundwater model. At the 200-ZP-1 OU, a suitable model was under development and was not available for comparison; however, because the primary intent was to estimate the difference in the extent of capture prior to and following remedy expansion, the absence of a model was not too limiting.

In each of the examples presented, assumptions that underlie the mapping method were violated to some degree. In each case, however, the analysis provided numerous water-level maps that reproduced (matched) measured water levels while reflecting the likely effects of pumping and/or changing river stage, as well as a single map that approximately depicts the extent of capture. In addition, the analyses identified areas where a relatively scarcity of water-level data might hinder evaluations of capture whether using the mapping technique or a model that is to be calibrated to groundwater levels.

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7 Conclusions

This document details a method for estimating the capture zone of one or more pumped wells under current or historic conditions based on water-level mapping, and it identifies software that incorporates the method. The method enables the experienced hydrogeologist to impart knowledge about certain aspects of the physical setting (e.g., the location and rates of pumped wells) when using automated interpolation to evaluate relatively large water-level data sets in a variety of settings.

The methods described are not suitable for use under all conditions and should typically not be used as the sole line of evidence of remedy performance. Appendices A and B describe simple evaluations of the potential effect of mild violations of the assumptions that underlie the mapping method on inferences of the extent of hydraulic capture. These results do not comprise a comprehensive evaluation of the impact of all underlying assumptions on capture inference under all conditions. It is likely that conditions encountered in the field will exhibit a combination of some or all of these effects. This reinforces the concept that the analysis of water-level data should constitute one of multiple lines of evidence in evaluating and optimizing pump-and-treat remedy performance.

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Appendix A

Verification of Method Implementation in Idealized Cases

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Appendix A
Verification of Method Implementation in Idealized Cases

This appendix presents the results of benchmarking tests completed to evaluate the performance of the water-level mapping technique at recovering idealized potentiometric surfaces calculated using a groundwater flow simulator. This appendix describes benchmarking of the point, line, and circular drift terms against simulations completed using MODFLOW-2000 (*MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process* [Harbaugh et al 2000]).

A1 Approach

A single-layer (i.e., two-dimensional) flow model constructed using MODFLOW-2000 is used to simulate uniform (i.e., planar) steady-state, constant tranmissivity flow upon which the following are superimposed:

- One point sink and one point source, representing one extraction well and one injection well
- Two line sinks, representing two interception trenches of equivalent unit strength
- A single circular source, representing a leaking pond.

Each of these drifts is compatible with the mapping of water levels in two dimensions. Each analysis is completed independently (i.e., the point sink/source case is simulated and evaluated independently of the link sink/source case, etc.). In each case, the MODFLOW-2000 simulations are used to produce error-free observations of the groundwater elevation at 40 randomly distributed hypothetical monitoring locations. These error-free water levels are then interpolated to a regular grid using (1) ordinary kriging and (2) universal kriging incorporating the corresponding drift term. The resulting mapped surfaces are compared with the ideal surface produced using MODFLOW-2000.

A2 Results of Verification Testing

A2.1 Point Sinks/Sources

This point sinks/sources drift term is typically used to account for mounding (or drawdown) of water levels in response to injection (or extraction) at a known rate at one or more wells.

Figure A-1 (map "a") presents a uniform hydraulic gradient simulated using MODFLOW-2000 in the absence of any sink/source features and the location of 40 hypothetical monitoring wells. Figure A-1 (map "b") presents steady-state groundwater levels simulated using MODFLOW-2000 when pumping at one extraction well and one injection well is superimposed on the uniform hydraulic gradient. Figure A-1 (map "c") presents the water levels that are obtained when heads obtained at the 40 hypothetical monitoring wells from Figure A-1 (map "b") are interpolated using ordinary kriging. Figure A-1 (map "d") presents the water levels that are obtained when heads obtained at the 40 hypothetical monitoring wells from Figure A-1 (map "b") are interpolated using universal kriging incorporating the point sink/source drift.

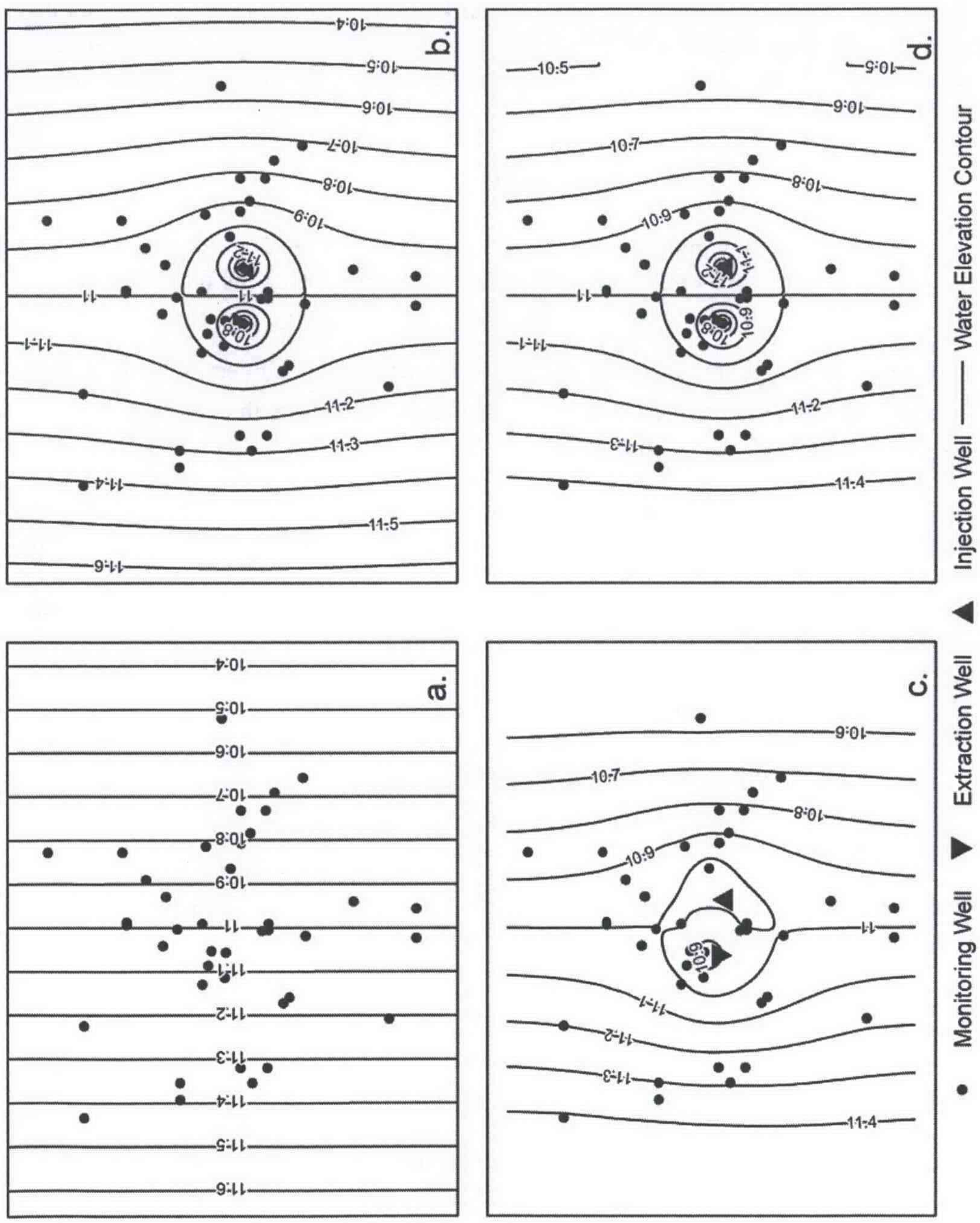


Figure A-1. Simulated and Mapped Water Levels for One Point Sink and One Point Source: (a) Configuration of Synthetic Model with Uniform Gradient and 40 Monitoring Locations, (b) Simulated Water Levels with One Injection and One Extraction Well, (c) Water Levels from Ordinary Kriging, and (d) Water Levels from Universal Kriging Incorporating Point Sink and Source Drifts

Figure A-1 (map “d”) recovers the potentiometric surface (as expected) with well-defined concentric contours centered on each of the wells. Figure A-1 (map “c”) depicts a surface that is similar in general appearance, with evidence for convergent flow to and divergent flow from the extraction and injection wells, respectively, but that lacks well-defined concentric contours around each of the wells. In addition, the highest and lowest elevations in the interpolated grid in the vicinity of the sink/source features are not centered on the known location of these features but instead are displaced from them and centered on the nearest monitoring locations that exhibit the highest and lowest elevations, respectively.

A2.2 Horizontal Line Sinks/Sources

The “horizontal line sinks/sources drift term is typically used to account for mounding (or drawdown) in response to horizontal linear features of known extraction (injection) rate, such as interception trenches or infiltration galleries.

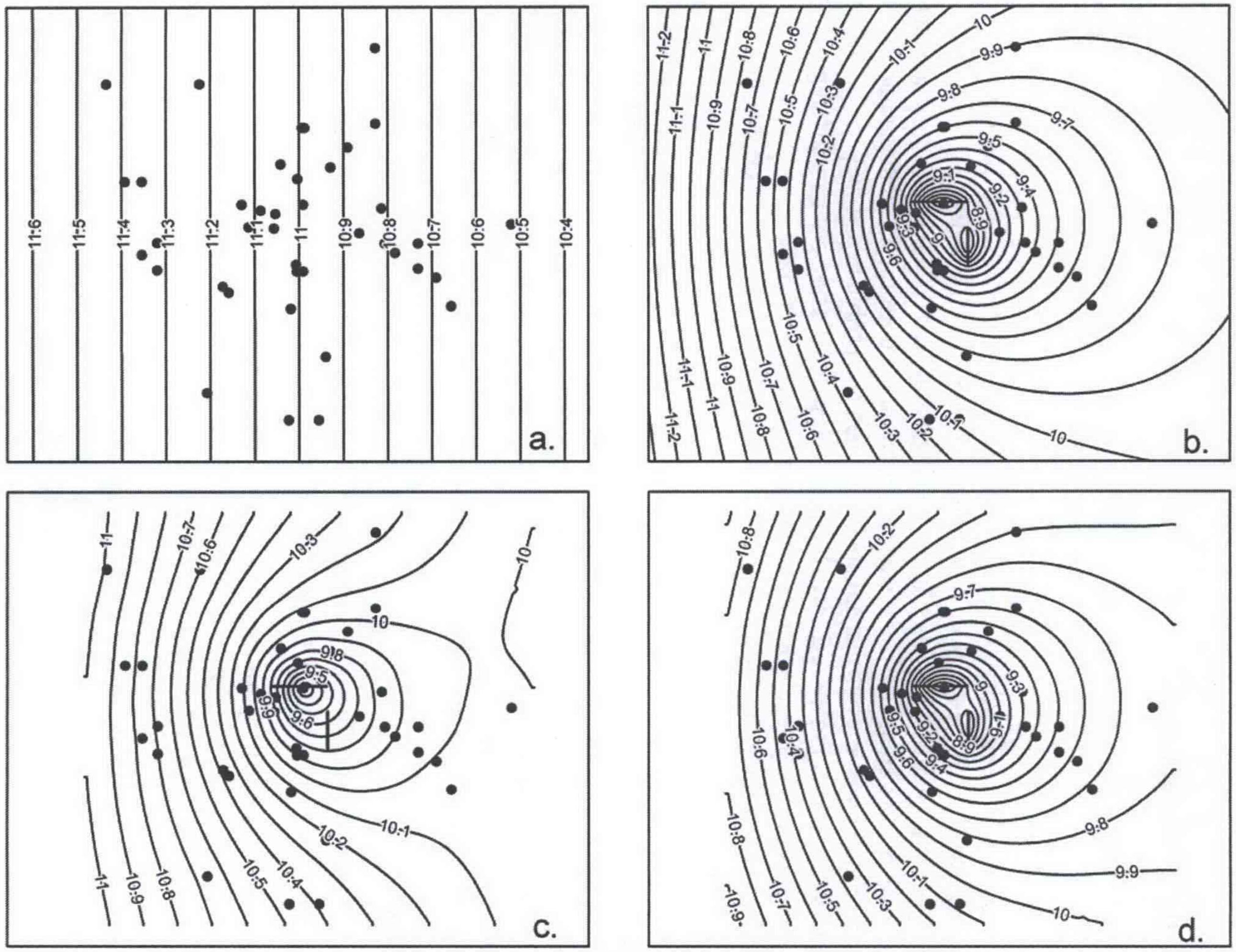
Figure A-2 (map “a”) presents a uniform hydraulic gradient simulated using MODFLOW-2000 in the absence of any sink/source features and the location of 40 hypothetical monitoring wells. Figure A-2 (map “b”) presents steady-state groundwater levels simulated using MODFLOW-2000 when groundwater interception at two line sinks of consistent unit rate is superimposed on the uniform hydraulic gradient. Figure A-2 (map “c”) presents the water levels that are obtained when heads obtained at the 40 hypothetical monitoring wells from Figure A-2 (map “b”) are interpolated using ordinary kriging. Figure A-2 (map “d”) presents the water levels that are obtained when heads obtained at the 40 hypothetical monitoring wells from Figure A-2 (map “b”) are interpolated using universal kriging incorporating the two line sinks.

Figure A-2 (map “d”) recovers the potentiometric surface with well-defined concentric contours centered on each of the line sink features. Figure A-2 (map “c”) depicts a surface that is similar in general appearance, with some evidence for convergent flow toward the line sink features. However, Figure A-2 (map “c”) lacks the well-defined concentric contours around each of the line sink features, and essentially shows no evidence of the smaller line sink due to the absence of a monitoring point close to this feature, and (despite the relatively large number of monitoring points) the absence of sufficient additional monitoring locations nearby to elucidate the effects of this feature.

A2.3 Circular Source

The “circular source” drift term is typically used to account for mounding of water levels in response to infiltration through the base of a pond that is approximately circular.

Figure A-3 (map “a”) presents a uniform hydraulic gradient simulated using MODFLOW-2000 in the absence of any sink/source features, and the location of 40 hypothetical monitoring wells. Figure A-3 (map “b”) presents steady-state groundwater levels simulated using MODFLOW-2000 when groundwater infiltration at a single circular source of uniform unit rate is superimposed on the uniform hydraulic gradient. Figure A-3 (map “c”) presents the water levels that are obtained when heads obtained at the 40 hypothetical monitoring wells from Figure A-3 (map “b”) are interpolated using ordinary kriging. Figure A-3 (map “d”) presents the water levels that are obtained when heads obtained at the 40 hypothetical monitoring wells from Figure A-3 (map “b”) are interpolated using universal kriging incorporating the circular source drift.



• Monitoring Well —— Line Sink —— Water Elevation Contour

Figure A-2. Simulated Water and Mapped Water Levels for Two Line Sinks: (a) Configuration of Synthetic Model with Uniform Gradient and 40 Monitoring Locations, (b) Simulated Water Levels with Two Line Sinks, (c) Water Levels from Ordinary Kriging, and (d) Water Levels from Universal Kriging Incorporating Two Line Sink Drifts

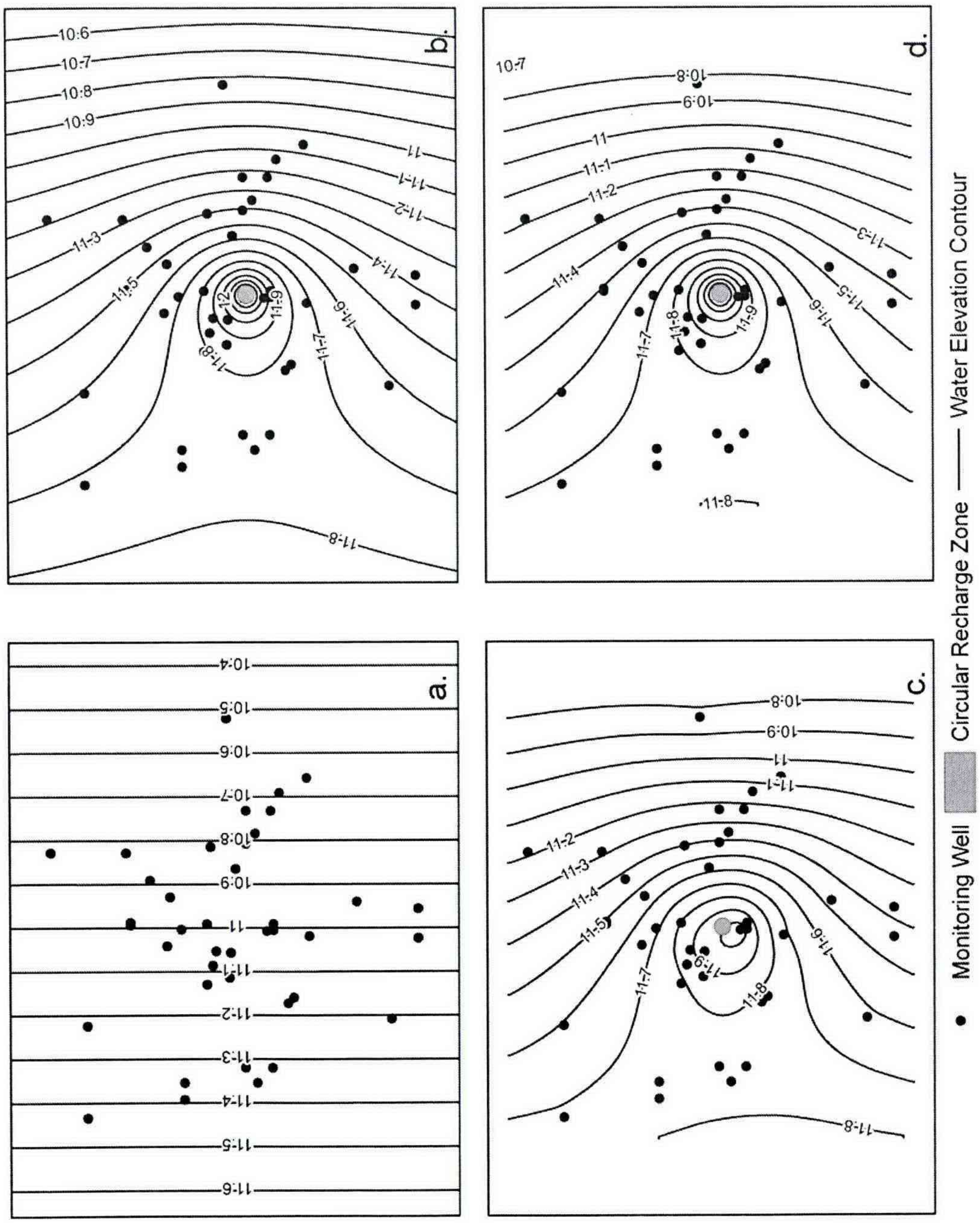


Figure A-3. Simulated and Mapped Water Levels for One Circular Source: (a) Configuration of Synthetic Model with Uniform Gradient and 40 Monitoring Locations, (b) Simulated Water Levels with One Circular Recharge Zone, (c) Water Levels from Ordinary Kriging and (d) Water Levels from Universal Kriging Incorporating a Circular Source Drift Term

Figure A-3 (map "d") recovers the potentiometric surface with well-defined concentric contours centered on the circular source feature. Figure A-3 (map "c") depicts a surface that is similar in general appearance, with some evidence for divergent flow away from the circular source feature. However, Figure A-3 (map "c") lacks the well-defined concentric contours around the circular source feature; the highest elevation in the interpolated grid in the vicinity of the circular source is not centered on this feature, but is displaced from it and centered on the nearest monitoring location exhibiting the highest elevation.

As described in the main text of this document, the circular source drift can be modified to account for drawdown in response to discharge of water at one or more circular features (e.g., a lake) by revising the form of the drift term to be a constant within the footprint of the circular feature. Since the time of writing, this drift term has not been used to prepare water-level maps, and the results of verification testing are not presented here.

A3 Reference

Harbaugh, A. W., E. R. Banta, M. C. Hill, and M. G. McDonald, 2000, *MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process*, Open File Rep. 00-92, U.S. Geological Survey, Reston, Virginia.

Appendix B

Empirical Evaluation of Limitations Deriving from Assumptions

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Appendix B
Empirical Evaluation of Limitations Deriving from Assumptions

This appendix presents results of tests completed to evaluate the potential impact of assumptions that underlie the water-level mapping method when it is used to interpolate potentiometric surfaces under non-ideal conditions. This appendix describes empirical evaluations of the potential impact of several key assumptions that underlie the mapping method for conclusions regarding the extent of capture inferred from water-level maps. The results presented are illustrative, and they do not comprise a comprehensive evaluation of the impact of all underlying assumptions on capture inference under all conditions. It is likely that conditions encountered in the field will exhibit a combination of some, or all, of these effects.

B1 Approach

The single-layer (i.e., two-dimensional) flow model constructed using MODFLOW-2000 (*MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process* [Harbaugh et al. 2000]), which is described in Appendix A, is also used for these evaluations. In each case, the MODFLOW-2000 simulations are used to produce observations of groundwater elevation at up to 40 randomly distributed hypothetical monitoring locations. These water levels are then interpolated to a regular grid using the mapping technique incorporating a point sink drift, and the resulting surfaces are compared with the ideal surface produced using MODFLOW-2000.

The following evaluations of the extent of capture, developed by a single point sink, are described:

- The first, steady-state, evaluation considers the effects of the following:
  - Decreasing saturated thickness approaching the extraction well in response to increasing extraction rates within an unconfined aquifer
  - Differing numbers of hypothetical monitoring locations for conditioning maps prepared for an unconfined aquifer.
- The second, non-steady (transient), evaluation considers the effect of obtaining the hypothetical water levels and estimating the extent of capture at times during which storage depletion is a significant source of water to an extraction well within an unconfined aquifer.
- The third, steady-state, evaluation considers the effect of attempting to estimate the extent of capture within a confined aquifer that is mildly heterogeneous.
- The fourth, steady-state, evaluation considers the effect of attempting to estimate the extent of capture within a confined aquifer when measurements and/or reporting of groundwater levels are not error-free.

Each analysis is completed independently (e.g., the potential effects of desaturation are evaluated independently of the potential effects of mild heterogeneity).

B2 Results of Empirical Evaluations

B2.1 Diminishing Transmissivity Within an Unconfined Aquifer

For this example, a single well extracts water from an unconfined aquifer. Steady-state flow is considered, so changes in storage are ignored. This evaluation considers the effect of increasing the extraction rate at the well (leading to increasing drawdown and, hence, diminishing transmissivity approaching the wells) while reducing the number of hypothetical locations at which error-free water-level measurements can be obtained. Accompanying each graphic that depicts visual results is the drawdown calculated within the model cell that contains the well when the well block correction of "Designing Pumped Well Characteristics into Electrical Analog Models" (Prickett 1967) is used as fraction of the initial saturated thickness within that cell.

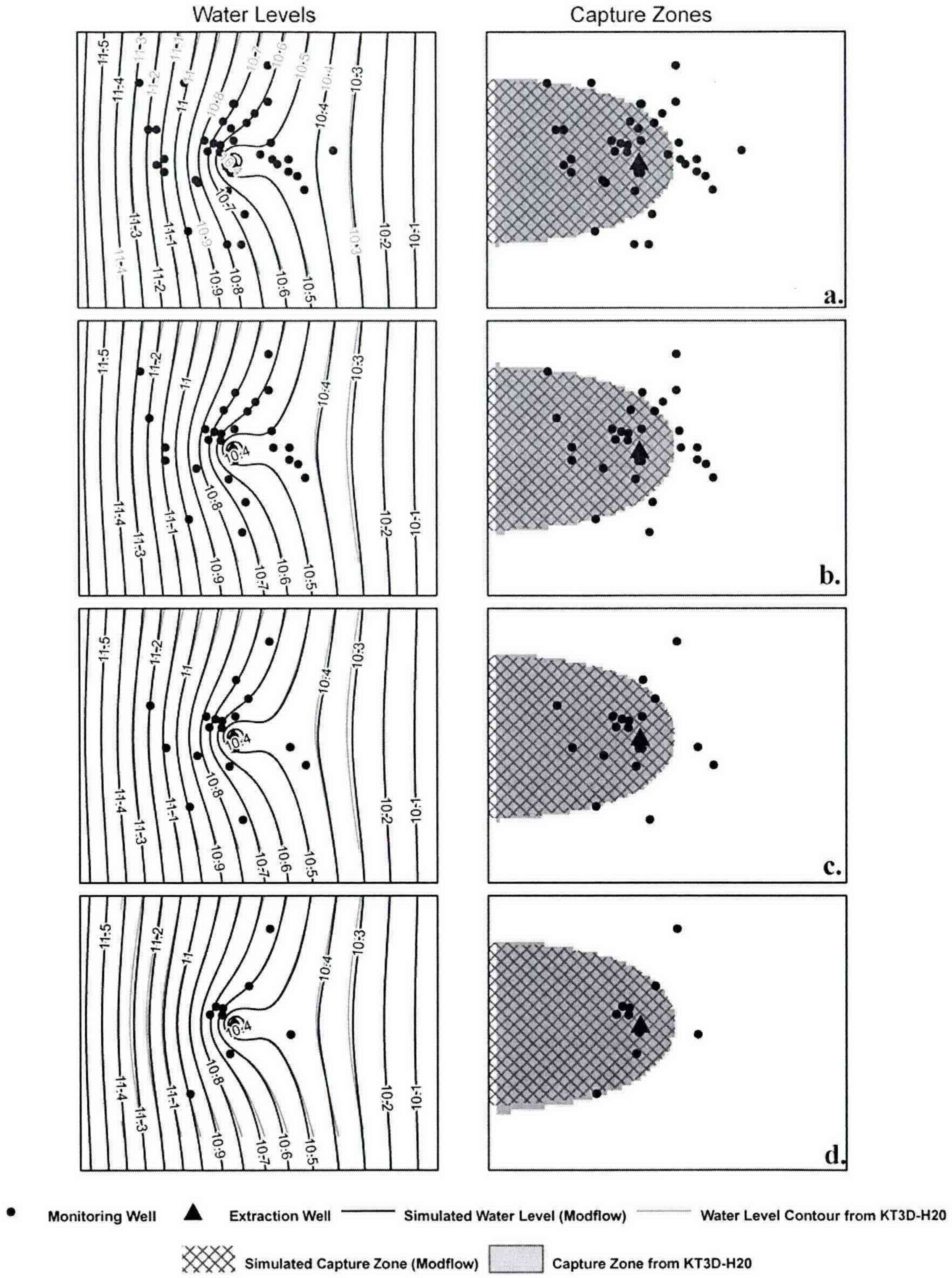
- Figure B-1 depicts water levels simulated under an extraction rate of 25 units (left panel) and those obtained using the mapping technique incorporating a single point sink, using 40 hypothetical monitoring locations (map "a"), 30 hypothetical monitoring locations (map "b"), 20 hypothetical monitoring locations (map "c"), and 10 hypothetical monitoring locations (map "d"). In this case, the corrected drawdown within the well cell is about 13.6 percent of the initial saturated thickness.

- Figure B-2 depicts water levels simulated under an extraction rate of 30 units (left panel) and those obtained using the mapping technique incorporating a single point sink, using 40 hypothetical monitoring locations (map "a"), 30 hypothetical monitoring locations (map "b"), 20 hypothetical monitoring locations (map "c"), and 10 hypothetical monitoring locations (map "d"). In this case, the corrected drawdown within the well cell is about 17 percent of the initial saturated thickness.

- Figure B-3 depicts water levels simulated under an extraction rate of 35 units (left panel) and those obtained using the mapping technique incorporating a single point sink, using 40 hypothetical monitoring locations (map "a"), 30 hypothetical monitoring locations (map "b"), 20 hypothetical monitoring locations (map "c"), and 10 hypothetical monitoring locations (map "d"). In this case, the corrected drawdown within the well cell is about 21.3 percent of the initial saturated thickness.

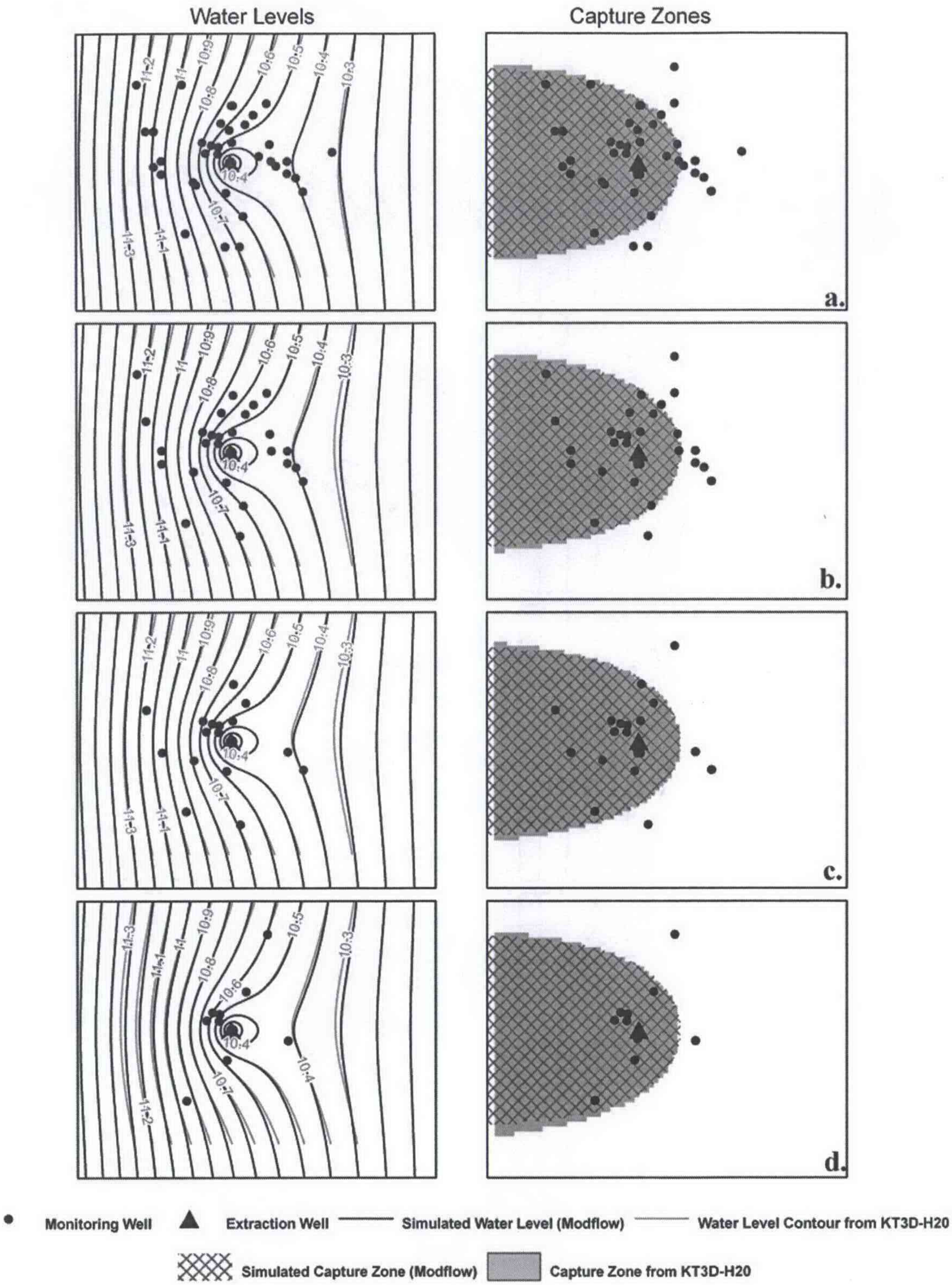
- Figure B-4 depicts water levels simulated under an extraction rate of 38 units (left panel) and those obtained using the mapping technique incorporating a single point sink, using 40 hypothetical monitoring locations (map "a"), 30 hypothetical monitoring locations (map "b"), 20 hypothetical monitoring locations (map "c"), and 10 hypothetical monitoring locations (map "d"). In this case, the corrected drawdown within the well cell is about 25.3 percent of the initial saturated thickness. Note that the well cell becomes "dry" at an extraction rate approaching 40 units.

Figures B-1 through B-4 suggest that the extent of capture estimated using the mapping method provides a reasonable estimate of the simulated ("true") capture for the range of conditions considered, with a slight tendency to over-predict these extents as the number of monitoring locations decreases. To further illustrate this, Figure B-5 depicts water levels simulated under four different extraction rates: (a) 25 units, (b) 30 units, (c) 35 units, and (d) 38 units, together with the corresponding mapped water levels prepared using five hypothetical monitoring locations (left panel). Figure B-5 also illustrates the corresponding modeled (true) and mapped (right panel) capture.



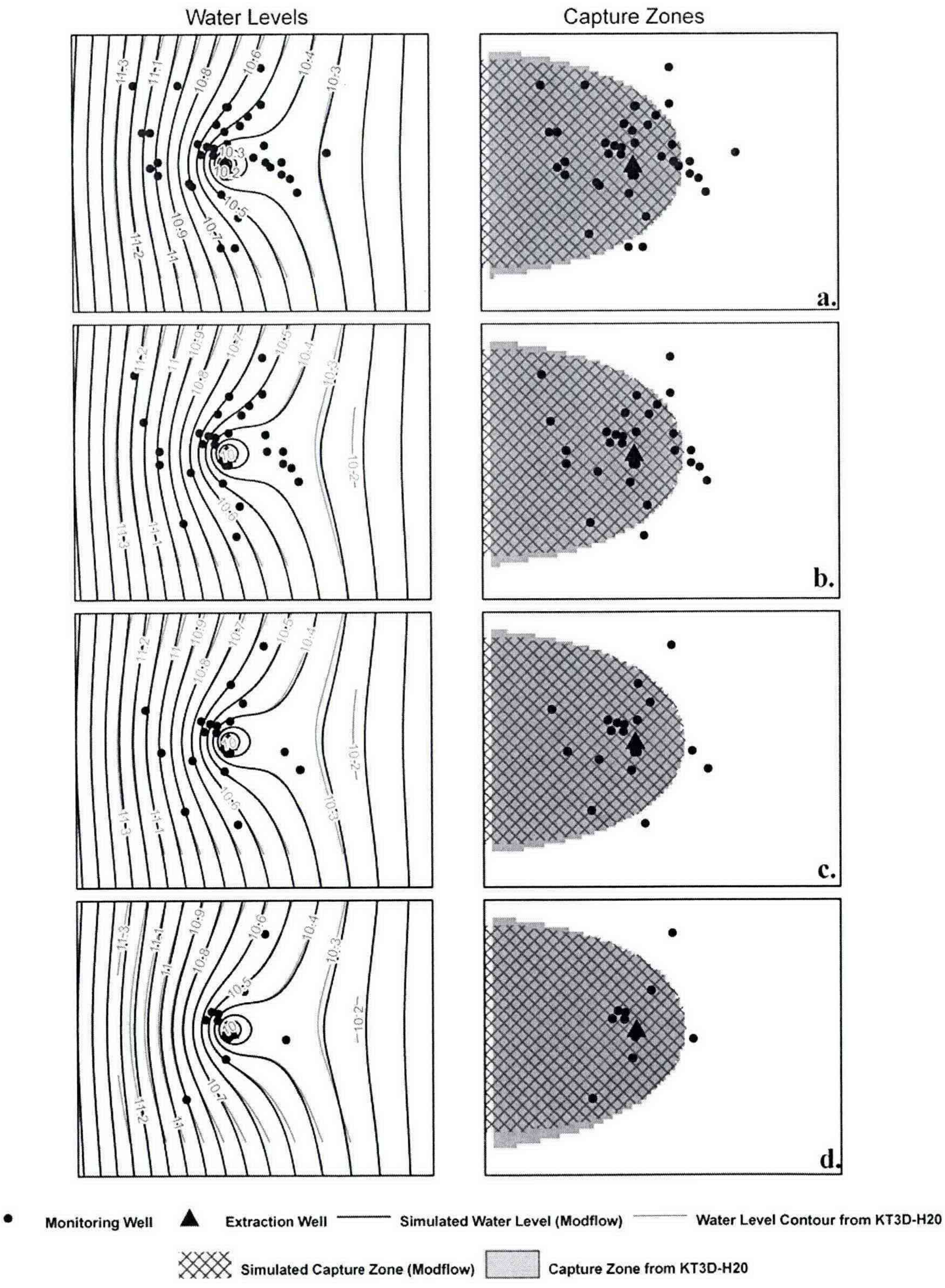
NOTE: Corrected drawdown is 13.6 percent of initial saturated thickness.

Figure B-1. Simulated and Mapped Water Levels for Q = 25 Units with (a) 40, (b) 30, (c) 20, and (d) 10 Monitoring Locations



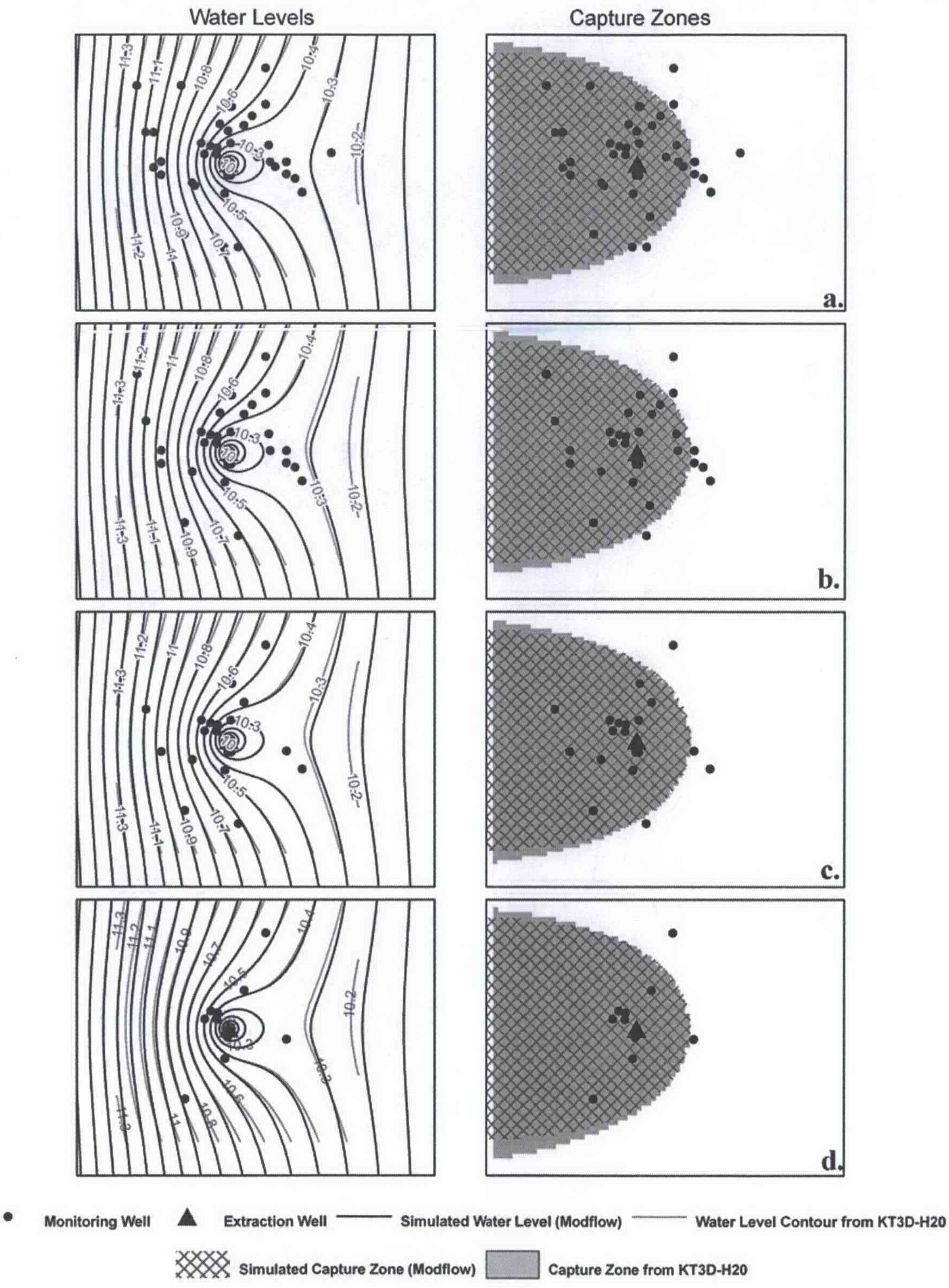
NOTE: Corrected drawdown is 17 percent of initial saturated thickness.

Figure B-2. Simulated and Mapped Water Levels for Q = 30 Units with (a) 40, (b) 30, (c) 20, and (d) 10 Monitoring Locations



NOTE: Corrected drawdown is 21.3 percent of initial saturated thickness.

Figure B-3. Simulated and Mapped Water Levels for Q = 35 Units with (a) 40, (b) 30, (c) 20, and (d) 10 Monitoring Locations



NOTE: Corrected drawdown is 25.3 percent of initial saturated thickness.

Figure B-4. Simulated and Mapped Water Levels for Q = 38 Units with (a) 40, (b) 30, (c) 20, and (d) 10 Monitoring Locations

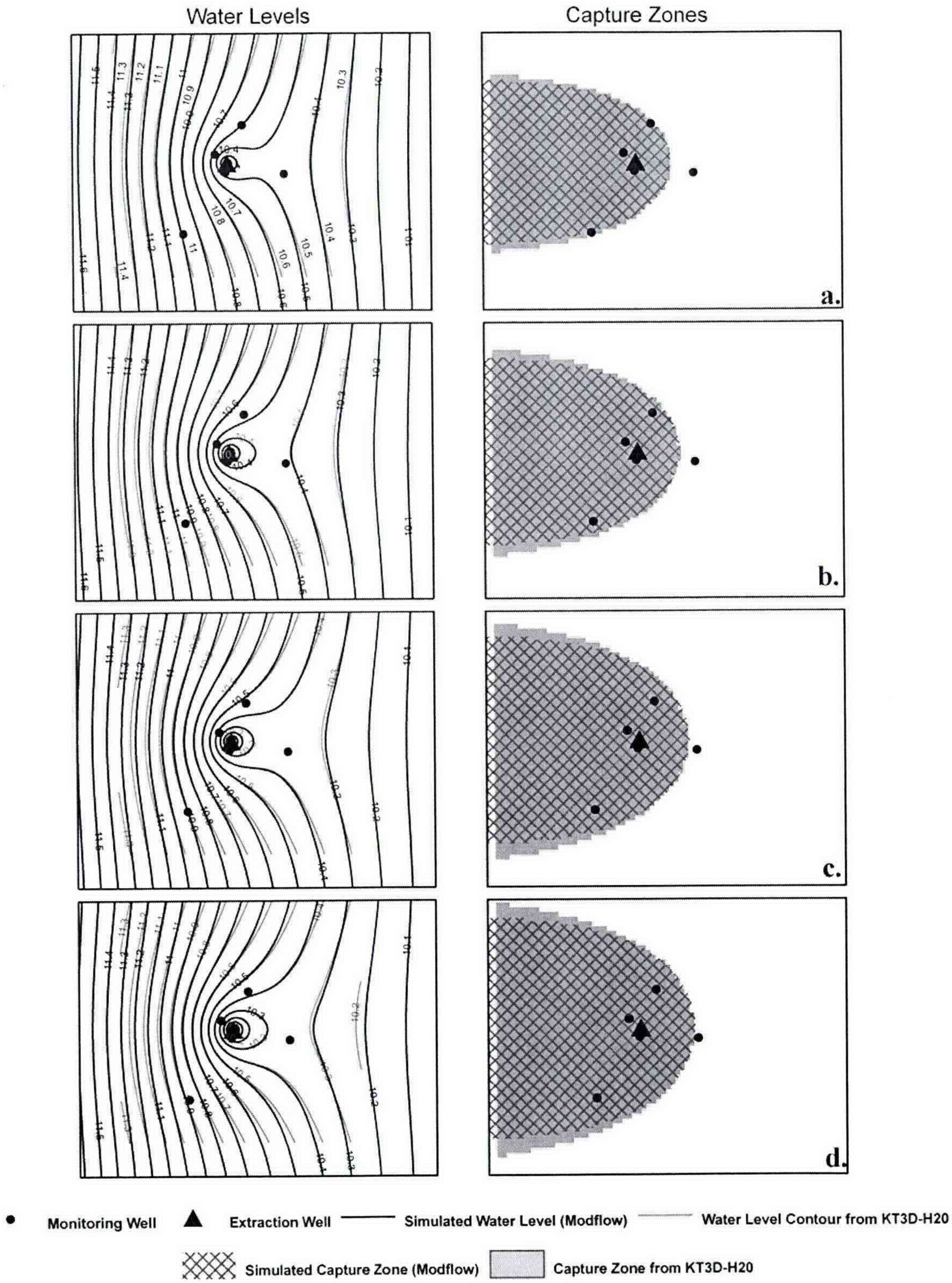


Figure B-5. Simulated and Mapped Water Levels Using Five Monitoring Locations for Q = (a) 25, (b) 30, (c) 35, and (d) 38 Units

B.2.2 Transient Conditions Within an Unconfined Aquifer

For this example, a single well extracts water at a constant rate of 38 units from an unconfined aquifer. Non-steady (transient) flow is considered, so changes in storage are significant. This evaluation considers the effect of obtaining hypothetical error-free water levels and estimating the extent of capture at times during which storage depletion rate is a significant fraction of the well extraction rate. Graphics depict the estimated extent of capture at various times together with the "true" steady-state extent of capture that is developed once storage depletion is negligible.

Figure B-6 illustrates the ratio of the storage depletion to the well extraction rate over time. Eight times are selected for obtaining and mapping groundwater levels and for estimating the extent of capture (these are indicated on the figure by vertical lines).

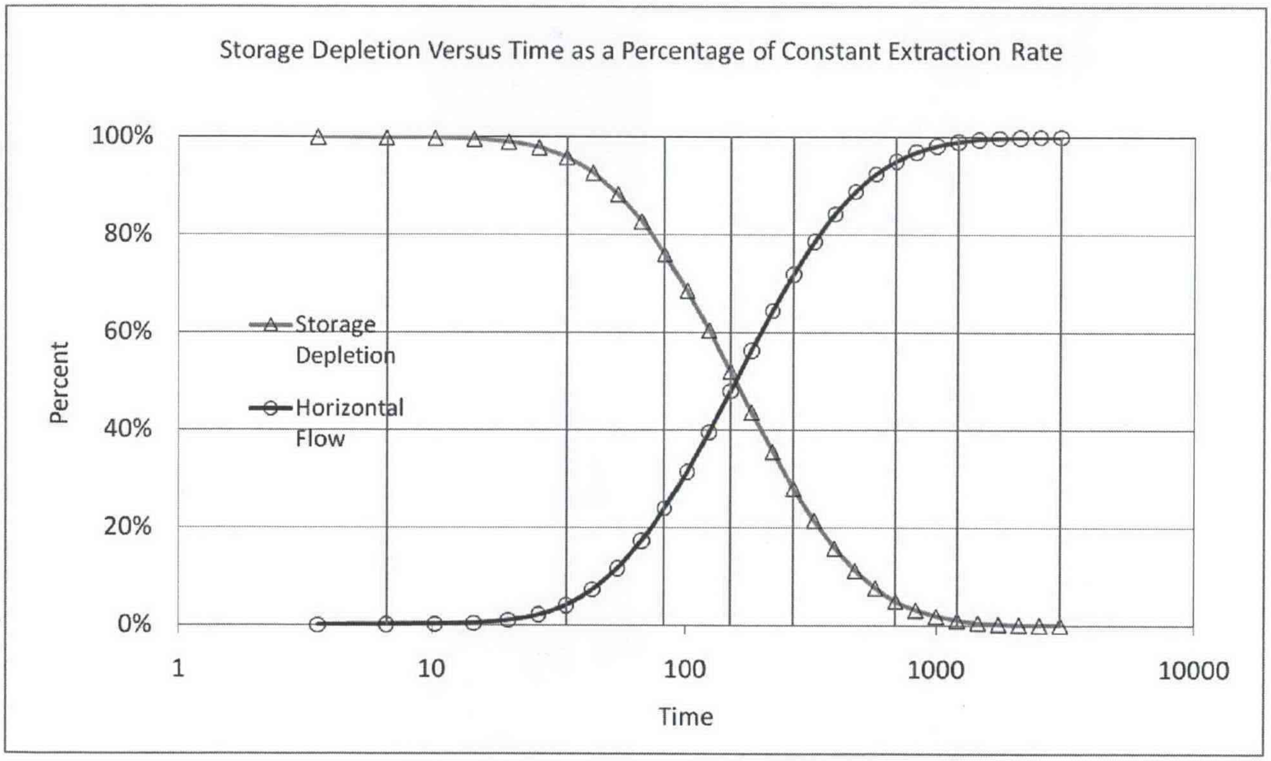


Figure B-6. Contribution of Storage Depletion to Extracted Water Versus Time

Figure B-7 presents simulated and mapped water levels obtained using 40 hypothetical monitoring locations at times when storage depletion constitutes about 99 percent (time = 6.6 units), 95 percent (time = 34 units), 75 percent (time = 83 units), and 50 percent (time = 150 units) of the well extraction rate. Figure B-8 presents simulated and mapped water levels obtained using the same 40 hypothetical monitoring locations at times when storage depletion constitutes about 28 percent (time = 270 units), 5 percent (time = 700 units), 1 percent (time = 1,200 units), and less than 1/100th of a percent (time = 3,000 units) of the well extraction rate.

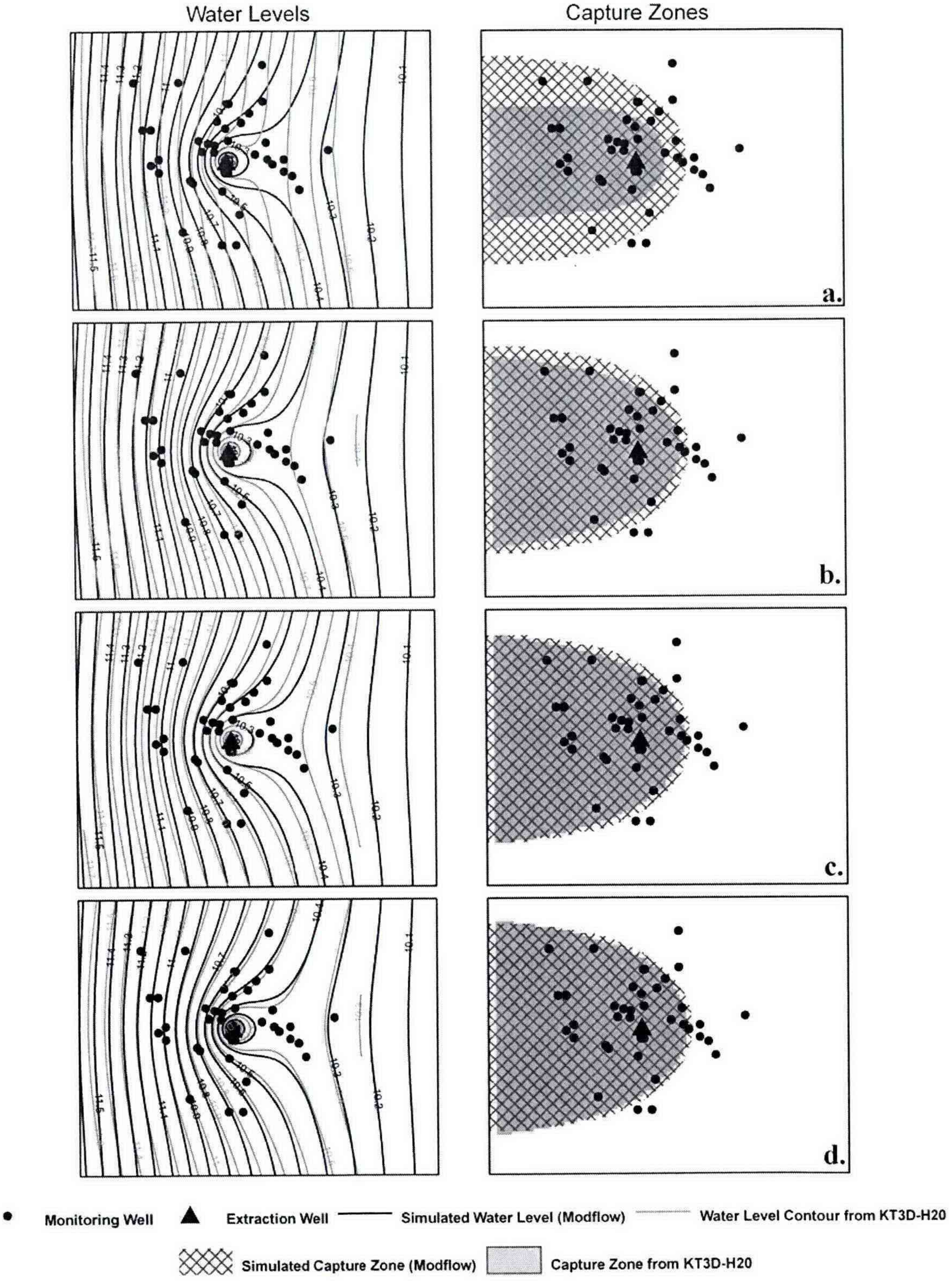


Figure B-7. Simulated and Mapped Water Levels for Q = 38 Units at Time (a) 6.6, (b) 33.8, (c) 82.6 and (d) 151.3

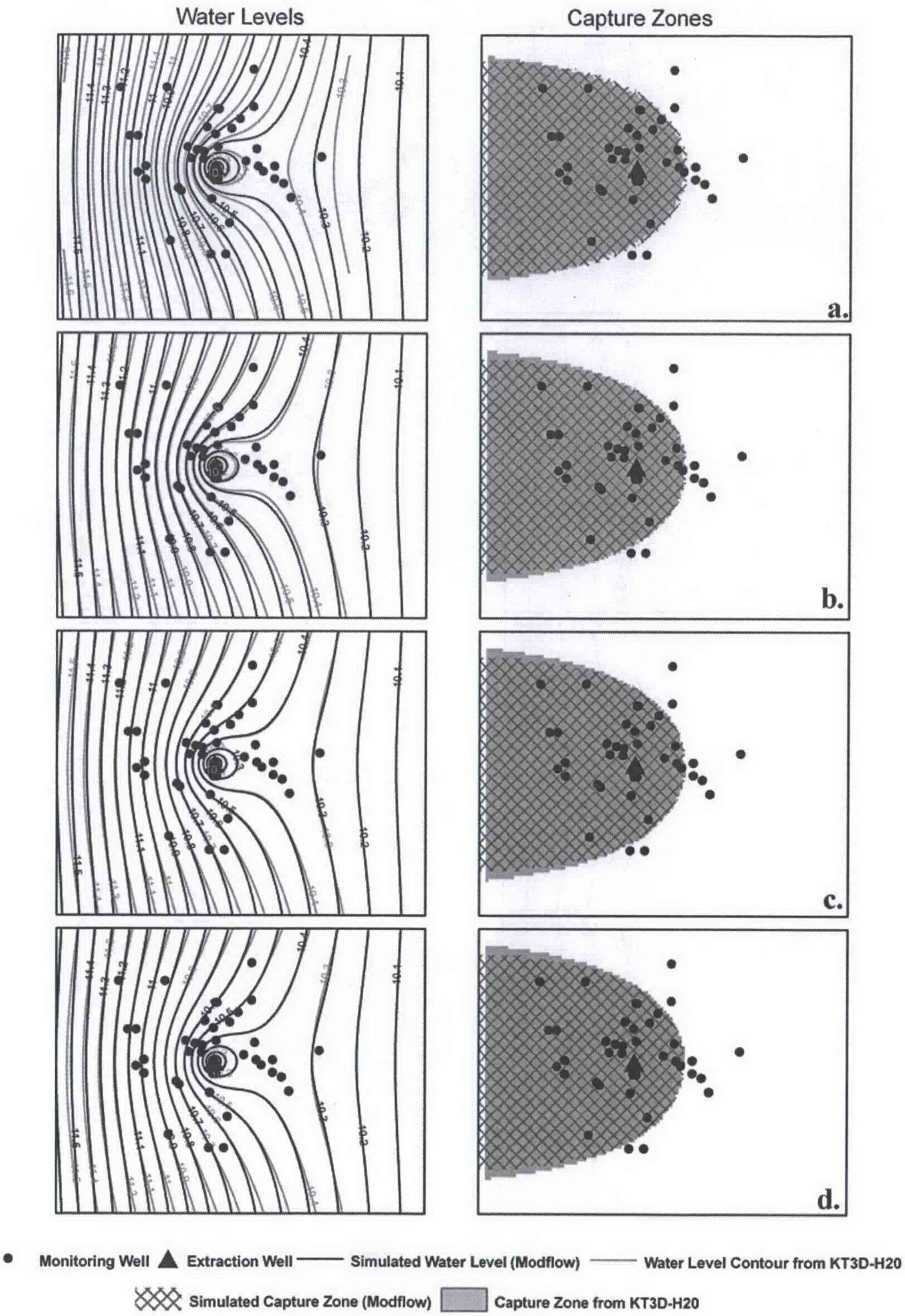


Figure B-8. Simulated and Mapped Water Levels for Q = 38 Units at Time (a) 269.9, (b) 689.0, (c) 1199.0, and (d) 3001.0

Figure B-6, Figure B-7 (maps "a" through "d"), and Figure B-8 (maps "a" through "d") suggest that as the rate of storage depletion decreases, the mapped extent of capture (based on water levels measured at the corresponding time) increases. From an intuitive perspective, this is consistent with the expectation that, ideally, quasi-steady radial flow toward the well should become established with increasing time, and suggests that the mapping method may reflect the increasing extent of hydraulic capture over time as quasi-steady conditions are attained. However, this result should not be over-interpreted as indicating that the mapping method correctly depicts the "instantaneous" extent of capture at any particular time, as such an evaluation has not currently been completed.

B2.3 Mild Heterogeneity Within a Confined Aquifer

For this example, a single well extracts water at a constant rate from a confined aquifer. Steady-state flow is considered, so the changes in storage are ignored. This evaluation considers the effect of obtaining hypothetical, error-free water levels and estimating the extent of capture within and aquifer possessing a geometric mean hydraulic conductivity of 10 units. Twenty random realizations of the heterogeneous aquifer hydraulic conductivity were obtained using the sequential Gaussian simulation program SGSIM (*GSLIB: Geostatistical Software Library and User's Guide* [Deutsch and Journel 1998]) using an isotropic spherical log-conductivity variogram with a range of 500 units and sill equivalent to 0.1, which leads to minimum and maximum hydraulic conductivities of about 1.0 and 100 units, respectively, over the 20 random realizations.

Figure B-9 presents simulated and mapped water levels (left panel) and simulated and mapped capture zones (right panel) obtained using four of the 20 random hydraulic conductivity fields. Figure B-9 suggests that the heterogeneous hydraulic conductivity fields produce perturbed or non-smooth simulated water-level contours, which in turn result in capture zones that (1) may not be oriented perpendicular to the page (as is the case for the homogeneous examples in earlier figures), and (2) exhibit perturbed (non-smooth) perimeters. Comparison of the mapped water-level contours, obtained using water-level observations at 40 monitoring locations, suggests that the mapped contours reflect the general orientation of the simulated "true" water levels but are typically smoother (less perturbed) than their simulated counterparts. This leads to mapped capture zones that are best described as "smoothed" representations of the "true" capture zones, reflecting their orientation and general extents but not some of the details at the margins. This is further illustrated in Figure B-10, which depicts the simulated ("true") and mapped capture frequencies calculated on the basis of the 20 random hydraulic conductivity fields.

B2.4 Imperfect Water-Level Measurements

For this example, a single well extracts water at a constant rate from a confined aquifer. Steady-state flow is considered, so the changes in storage are ignored. This evaluation considers the effect of estimating the extent of capture using water levels that are accompanied by measurement and/or reporting error that can be described by zero-mean normal distributions possessing standard deviations of 0.01 and 0.05 units, respectively. Twenty random realizations of these random errors were obtained for each error distribution and added to the "true" (i.e., error-free) water-level measurements. Water-level mapping and capture zone calculations were then completed for each individual data set and combined to construct capture frequency maps for each of the two error distributions.

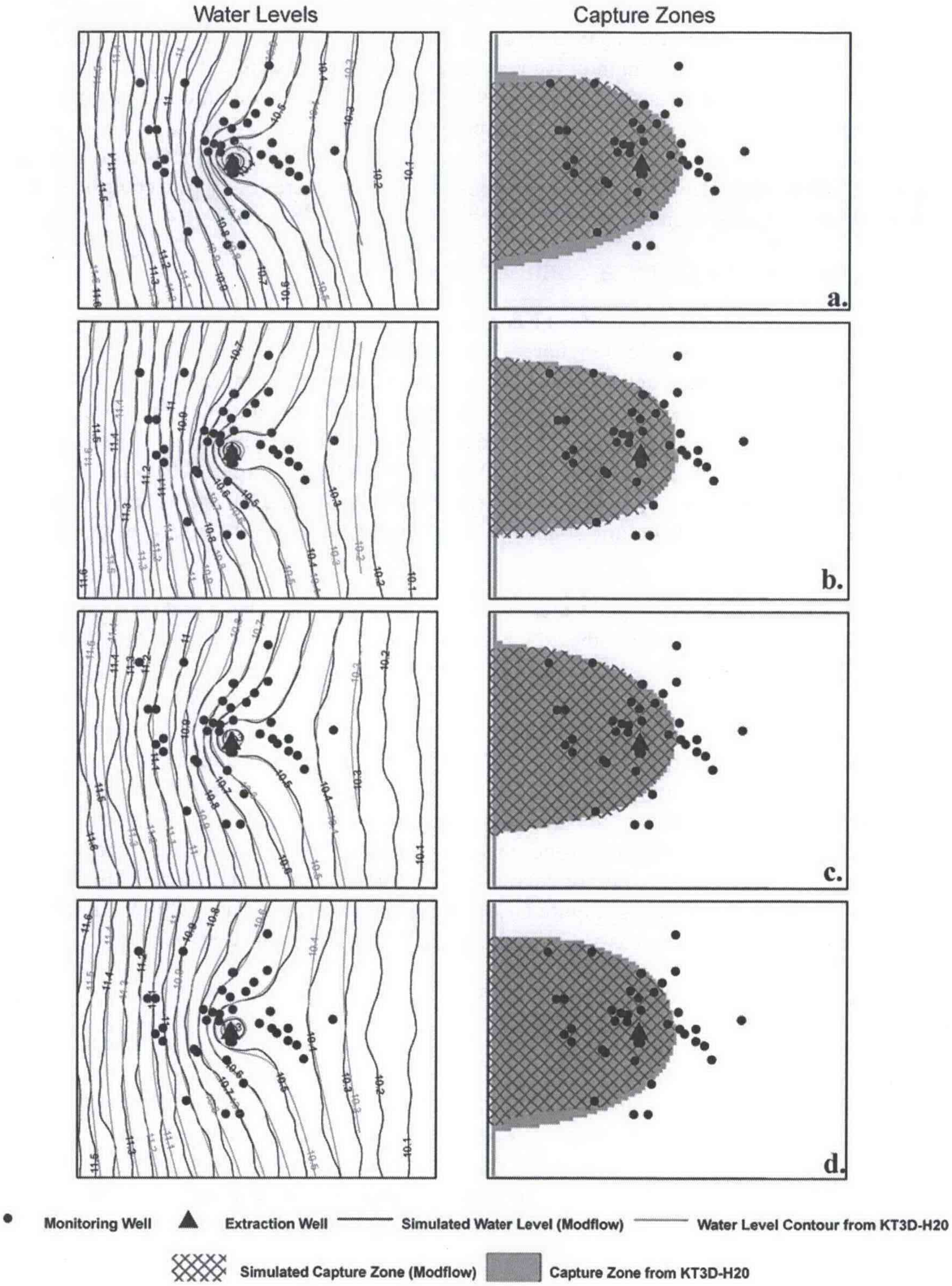


Figure B-9. Four Examples of Simulated and Mapped Water Levels and Hydraulic Capture Within a Mildly Heterogeneous Confined Aquifer Exhibiting a Log-Conductivity Variance of 0.1 Units

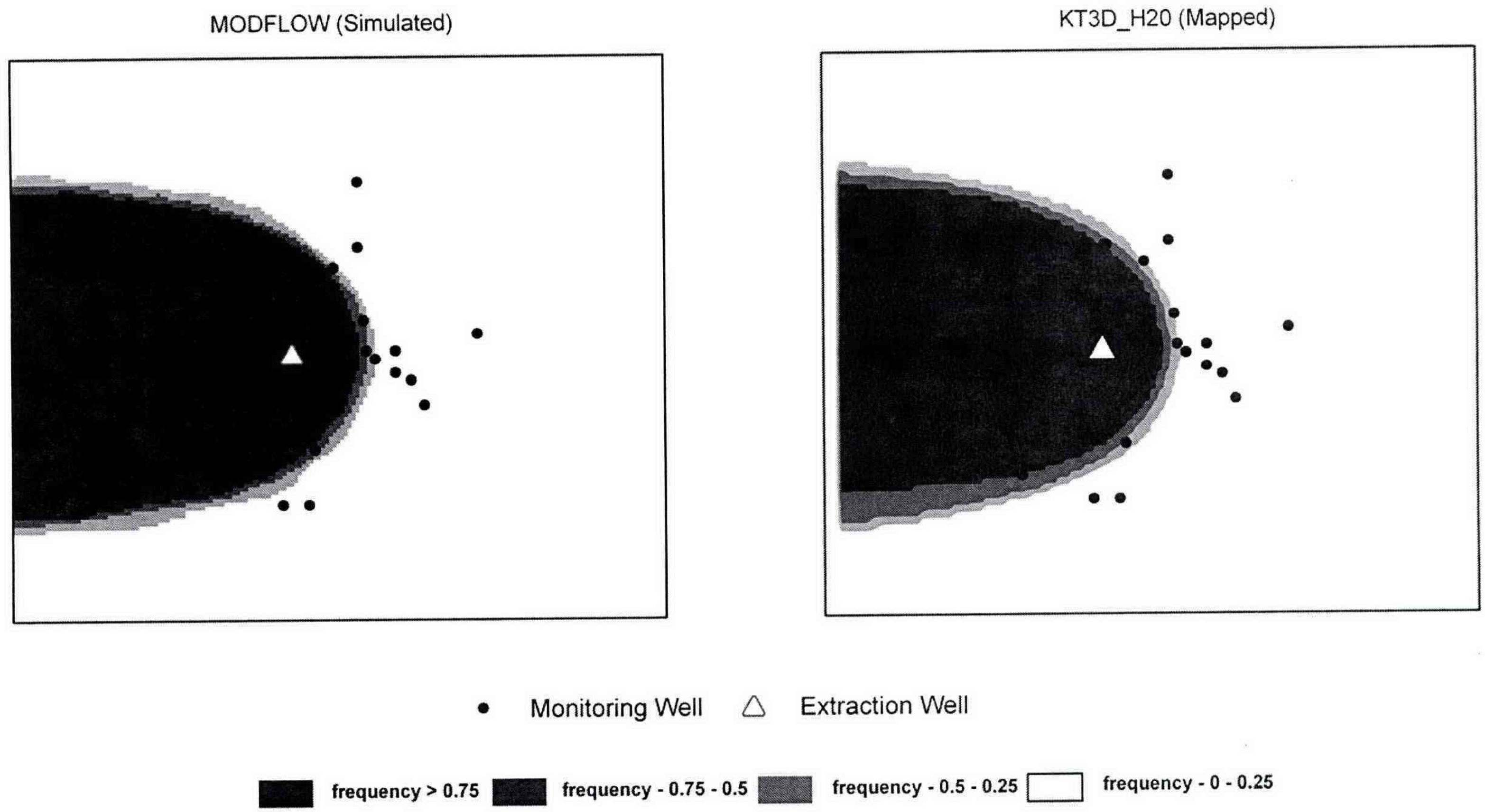


Figure B-10. Simulated ("True") and Mapped Capture Frequencies Within a Mildly Heterogeneous Confined Aquifer Exhibiting a Log-Conductivity Variance of 0.1 Units (Prepared Using 20 Random Conductivity Fields)

Figure B-11 presents the simulated "true" extent of hydraulic capture together with the capture frequencies that are obtained using the mapping method for each of the two error distributions. Figure B-11 suggests that on both occasions (i.e., for both the relatively accurate water-level measurements and the relatively less accurate water-level measurements), the higher capture frequencies reasonably reflect the "true" extent of capture, while the lower capture frequencies tend to over-predict the extent of capture. This is particularly evident in the case of relatively less accurate water-level measurements, where the extent of low capture frequencies is considerably larger than the extent of high capture frequencies.

This finding is consistent with an intuitive expectation that random measurement errors should, on average, result in unbiased estimates of the size and orientation of the true capture zone, and is one of the motivations for developing the capture frequency map technique and focusing evaluations of capture on the location and extents of relatively high and relatively low mapped frequencies.

B3 References

Deutsch, C., and A. Journel, 1998, *GSLIB: Geostatistical Software Library and User's Guide*, Oxford University Press, New York.

Harbaugh, A. W., E. R. Banta, M. C. Hill, and M. G. McDonald, 2000, *MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process*, Open File Report 00-92, U.S. Geological Survey, Reston, Virginia.

Prickett, T. A., 1967, "Designing Pumped Well Characteristics into Electrical Analog Models," in *Ground Water*, 5(4):38-46.

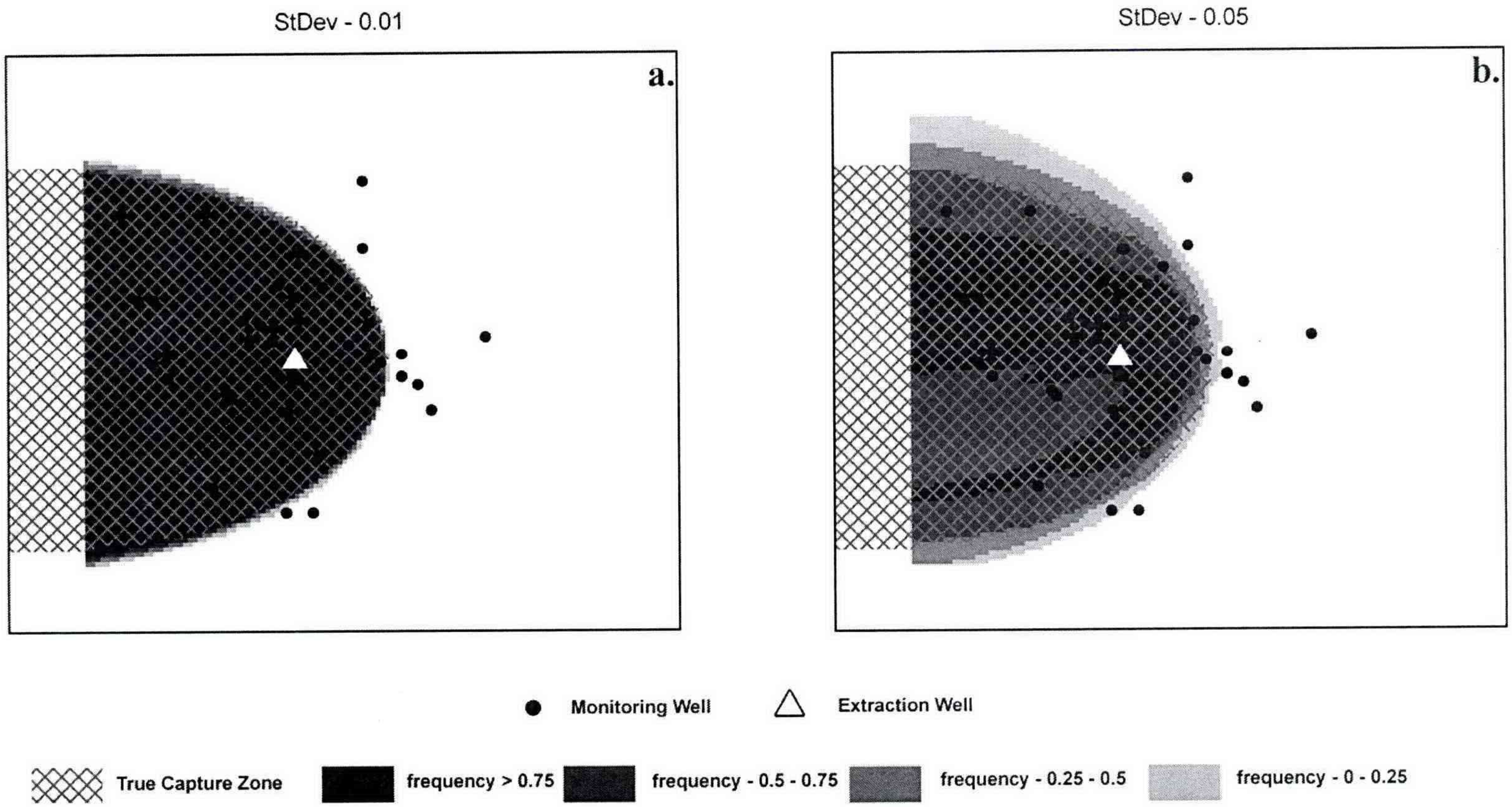


Figure B-11. Simulated ("True") Capture and Mapped Capture Frequency Within a Confined Aquifer Using Water-Level Measurements Accompanied by a Random Error of Standard Deviation (a) 0.01 Units and (b) 0.05 Units (Prepared Using 20 Random Water-Level Sets

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